EXAMINING THE EFFECTS OF SPACE FLIGHT ON THE HEART, LUNGS, AND BLOOD VESSELS

CARDIOVASCULAR ADAPTATION TO MICROGRAVITY

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INTRODUCTION

Which of the following space flight stresses (Figures 1 - 6) do you feel has the greatest overall effect on the functioning of the cardiovascular system during space flight? (Remember, cardio = heart and vascular = arteries and veins, all relating to the flow of blood around the body.)

Figure 1. The lack of gravity, which allows a shift of body fluids toward the head.

Figure 2. The stress of a high acceleration rate at launch.

Figure 3. Stress due to cramped quarters and lack of privacy on the shuttle.

Figure 4. The effects of higher radiation exposure away from the Earth.

Figure 5. Stress of reentry and landing.

Figure 6. Lack of exercise and weightlessness of objects, causing loss of muscle mass during flight.

The truth is all the different aspects of space flight shown in Figures. 1 - 6 may have an effect on the functioning of the cardiovascular system. Scientists do not yet have enough data from space to tell exactly what causes the cardiovascular system to change during space flight, but there is plenty of evidence to tell that it does change the way it operates, even on a short journey into space. All the information we have suggests that these changes are "normal"; in other words, the operation of the cardiovascular system changes from an "Earth normal" condition to a "space normal" condition as it adapts to the new environment of space.

In this chapter, we will be examining an actual space flight investigation that was designed by Dr. Gunnar Blomqvist, the principal investigator, and his colleagues at the University of Texas Southwestern Medical Center in Dallas, Texas. This experiment, which flew on both the SLS-1 mission and the SLS-2 mission, was designed to examine the cardiovascular consequences of the **fluid shift** that occurs during space flight in order to determine how the operation of the cardiovascular system is changed in space when astronauts are at rest and when they are exercising. The results of this study have provided us with important information about what happens to the human heart and the cardiovascular system during space flight, how it adapts to the space environment, and how long it takes to adapt. This study also examined the problems caused by this adaptation process when space travelers return to Earth.

Before we begin to examine what we have learned from Dr. Blomqvist's study about how the heart, lungs, and blood vessels work together in space, it is important to understand how these important components of the body normally function on Earth. We will look at how the heart and blood vessels act as a superhighway to transport the blood and nutrients to every cell in the body and to carry away the carbon dioxide and other waste products of the cells. We will also examine how the lungs operate to supply the blood with the most important element that it will carry to the cells: **oxygen**.

Figure 12

Earth Physiology

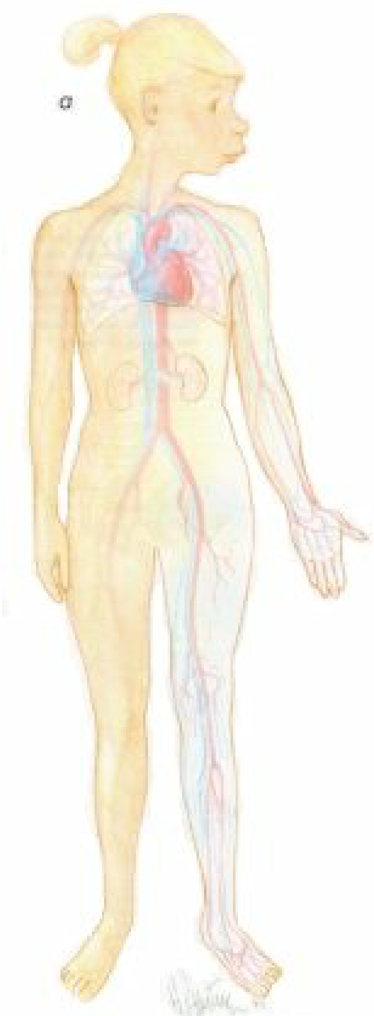
As you probably know, all the actions and movements of your body (and even your ability to think) depend on the delivery of oxygen and nutrients to the cells in your body on a constant basis. The heart is the main pump that forces the blood through the bl ood vessels of the body. The blood vessels form a closed system of "highways" that transport blood and allow the exchange of gases, nutrients, and wastes between the blood and the body cells. An estimated 62,000 miles of blood vessels throughout the body of an adult ensure that a continuous supply of nutrients and oxygen reaches each of the trillions of living cells and that waste products are carried away. The blood cells, specifically the red blood cells, serve as the "vehicles" that travel the blood-vessel highway to deliver oxygen (O_2) and to pick up the carbon dioxide (CO_2) from each cell. The lung is the "gas station," where the red blood cells drop off the CO_2 and refuel with O_2 to continue their journey among the cells. In this section, we will first examine the structure and function of the heart and the circulation. We will then build our story to include how the exchange of gases takes place between the blood and the lungs.

The Heart and the Circulation

The primary function of the heart is to pump blood through blood vessels to the body's cells. Imagine a simple machine like a water pump working for perhaps 70 or more years without attention and without stopping. Impossible? Yet this is exactly what the heart can do in our bodies. The heart is really a muscular bag surrounding four hollow compartments, with a thin wall of muscle separating the left hand side from the right hand side. The muscles in the heart are very strong because they have to work harder than any of the other muscles in our body, pushing the blood to our head and feet continuously.

The blood flow around our body is called our **circulation.** The heart connects the two major portions of the circulation's continuous circuit, the **systemic circulation** and the **pulmonary circulation.** The blood vessels in the pulmonary circulation carry the blood through the lungs to pick up oxygen and get rid of carbon dioxide, while the blood vessels in the systemic circulation carry the blood throughout the rest of our body (Figure 7).

Figure 8a. The cardiovascular system.



The heart actually has two separate sides, one designed to pump **deoxygenated** blood into the pulmonary circulation where the blood becomes **oxygenated,** and one designed to pump the oxygenated blood into the systemic circulation where the blood flows throughout the body (Figure 8a). Each side of the heart has two chambers or compartments. The top chamber on each side is called the **atrium.** The right atrium receives incoming deoxygenated blood from the body and the left atrium receives incoming oxygenated blood from the lungs. The thin-walled atrium on each side bulges as it fills with blood, and as the lower heart muscle relaxes, the atrium contracts and squeezes the blood into a second chamber, the thick muscular **ventricle.** The ventricle is the pumping chamber that, with each muscular contraction, pushes the blood forcefully out and into the lungs (right ventricle) and the rest of the body (left ventricle).

The atrium and ventricle on each side of the heart are separated by tissue flaps called **valves.** The structure of these valves prevents blood from flowing backward into the atrium as the ventricle squeezes blood out. The valve on the right side, between the atrium and the ventricle, is called the **tricuspid valve.** The valve on the left side, between the atrium and the ventricle, is called the **bicuspid** or **mitral valve.** There are two other important valves that help to keep the blood Rowing in the proper direction. These two valves are located at the two points where blood exits the heart. The **pulmonary valve** is located between the right ventricle and the pulmonary artery that carries the deoxygenated blood from the heart to the lungs, and the **aortic valve** is located between the left ventricle and the aorta, the major artery that carries the oxygenated blood from the heart to the rest of the body.

The **arteries** are the blood vessels that transport blood out of the heart under high pressure to the tissues. The **arterioles** are the last small branch of the arterial system through which blood is released into the **capillaries**. The capillaries are very small, thin-walled blood vessels where the exchange of gases, nutrients, and waste takes place between the cells and the blood. Blood flows with almost no resistance in the larger blood vessels, but in the arterioles and capillaries, considerable resistance to flow does occur because these vessels are so small in diameter that the blood must squeeze all its contents through them. The **venules** collect blood from the capillaries and gradually feed into progressively larger veins. The **veins** transport the blood from the tissues back to the heart. The walls of the veins are thin and very elastic and can fold or expand to act as a reservoir for extra blood, if required by the needs of the body.

Let us follow a single red blood cell (RBC) through one full cycle along the circulatory pathway (Figure 8b). Remember that RBCs carry oxygen throughout the body. Since the blood travels endlessly, an arbitrary choice must be made of a starting point to describe the RBC's route. We will begin at the point where the RBC has delivered its oxygen to a cell in need and is on its return back to the heart.

1. Once the **deoxygenated red blood cell (RBC)** returns to the heart, it enters either through the **superior vana cava** or the **inferior vena cava**. The superior vena cava returns deoxygenated blood from the **upper** part of the body to the heart. The inferior vena cava returns deoxygenated blood from the **lower** part of the body to the heart. These large veins lead into the right atrium.

2. The RBC passes through the tricuspid valve into the right ventricle.

3. The RBC is then pumped through the pulmonary valve into the pulmonary artery and on to the lungs. There the RBC gives off carbon dioxide and picks up oxygen.

4. The RBC returns to the heart through a pulmonary vein, enters the left atrium, passes through the mitral valve, and flows into the left ventricle.

5. The left ventricle pumps the fully oxygenated RBC through the aortic valve, into the **aorta**, the body's main artery, and out to the body.

6. From the aorta, the RBC flows into one of the many arteries of the body, through the arterioles, and then to the capillaries, where the RBC will deliver oxygen and nutrients to the cells and remove wastes and carbon dioxide. Next it moves through the venules, veins, and on to the vena cava in a deoxygenated state, and returns to the heart, only to begin its repetitive journey once again. **This whole process has taken approximately 20 seconds!**

That single RBC will travel about 950 miles (more than 1500 kilometers) in its brief 4-month lifetime!

Blood Pressure, Flow, and Resistance

Any fluid driven by a pump, and flowing in a circuit of closed channels, necessarily operates under pressure. Blood flowing in the body's circulatory system is an example of such a pressure-driven flow system. The **blood pressure**, in a blood vessel, is defined to be the force exerted by the blood against the vessel wall. It is this pressure caused by the pumping of the heart that keeps your blood circulating. Every blood vessel in the circulatory system has its own blood pressure, which changes continually. Even so, the term blood pressure is most commonly used to refer to **arterial pressure**.

Arterial blood pressure rises and falls in a pattern corresponding to the phases of the cycles of the heart, the **cardiac cycle**. That is, when the ventricles contract (ventricular **systole**), their walls squeeze the blood inside their chambers and force it into the pulmonary artery and aorta. As a result, the pressures in these arteries rise sharply. The maximum pressure achieved during such a ventricular contraction is the **systolic pressure**. When the ventricles relax (ventricular **diastole**), they begin to fill with blood again to prepare for the next contraction and the arterial pressure drops. The lowest pressure that remains in the arteries before the next ventricular contraction is termed the **diastolic pressure**.

Arterial blood pressure is usually only measured indirectly in healthy people. The method used to measure blood pressure involves placing a pressurized cuff around the arm to detect the force of blood pulsing through the arm's blood vessels. Blood pressure is normally expressed in units of millimeters of mercury (mm Hg). A blood pressure of 100 mm Hg means that the force exerted by the blood is sufficient to push a column of mercury up to a height of 100 mm (Figure 9). An actual column of mercury is rarely used; instead, an **analog** pressure scale is used that reflects the pressure measurement in similar units of mm Hg.A

When you have your blood pressure measured at the doctor's office, you will normally be told that your blood pressure is something like 120/80 mm Hg. Although the doctor calls it your blood pressure, it is actually your arterial pressure. It represents how hard your blood is being forced out by your left ventricle (systolic pressure at 120 mm Hg) and how the ventricles are preparing for the next contraction (diastolic pressure at 80 mm Hg).

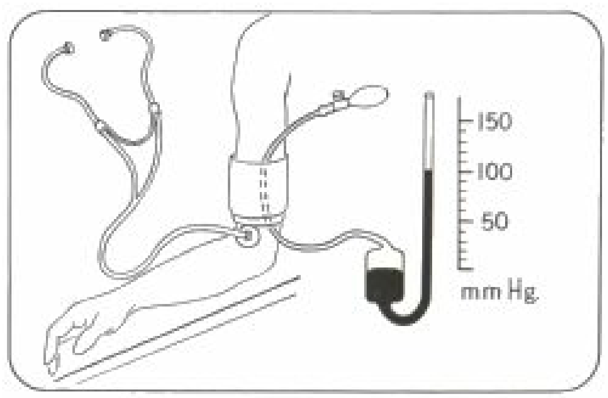


Figure 9. The original measurement scale used to measure blood pressure was the column of mercury. A less cumbersome analog scale is used today.

The surge of blood entering the arteries during a ventricular contraction causes the elastic walls of the arteries to swell (expand), but the pressure drops almost immediately as the ventricle completes its contraction and the arterial walls recoil (shrink back to normal size). This alternating expansion and recoil of an arterial wall can be felt as a **pulse** in an artery that runs close to the surface of the skin. The radial artery, for example, runs its course near the surface at the wrist and is commonly used to determine a person's **radial pulse**.

The radial pulse rate is normally equal to the rate at which the left ventricle is contracting, which is why it is used to determine **heart rate** (how fast your heart is beating) quickly and easily. A pulse also can reveal something about blood pressure, because an elevated pressure produces a pulse that feels full, while a low pressure is accompanied by a pulse that is easily compressed.

Flow through a blood vessel is determined by two factors: (1) the force that pushes the blood through the vessel, and (2) the **resistance** of the vessel to the blood flow. Ordinarily, the rate of blood flow is measured in milliliters or liters per minute (ml/min or l/min). The blood flow in the entire human circulation is about 5000 ml/min at rest in an average sized adult, but may be 5-6 times as great during heavy exercise when the body needs more oxygen to fuel that exercise. The amount of blood pumped by the heart in one minute is called the **cardiac output**.

It is important to note that the flow of blood in the body is directly influenced by gravity. When a person is standing, gravity helps pull the blood downward to the lower extremities. Without gravity, blood tends to remain closer to the heart. The force of gravity also makes it more difficult for the blood to flow upward to return to the heart and lungs for more oxygen. Our bodies have evolved to deal with the ever-present downward force of gravity; our leg muscles function as secondary pumps to help in the process of **venous return** which is blood flow back to the heart, also referred to as cardiac input). During walking or other leg movements, the muscles contract, forcing blood up through the veins of the calf toward the heart. The valves in the veins are arranged so that blood flows only in one direction (Figure 10). This mechanism effectively counteracts the force of gravity.

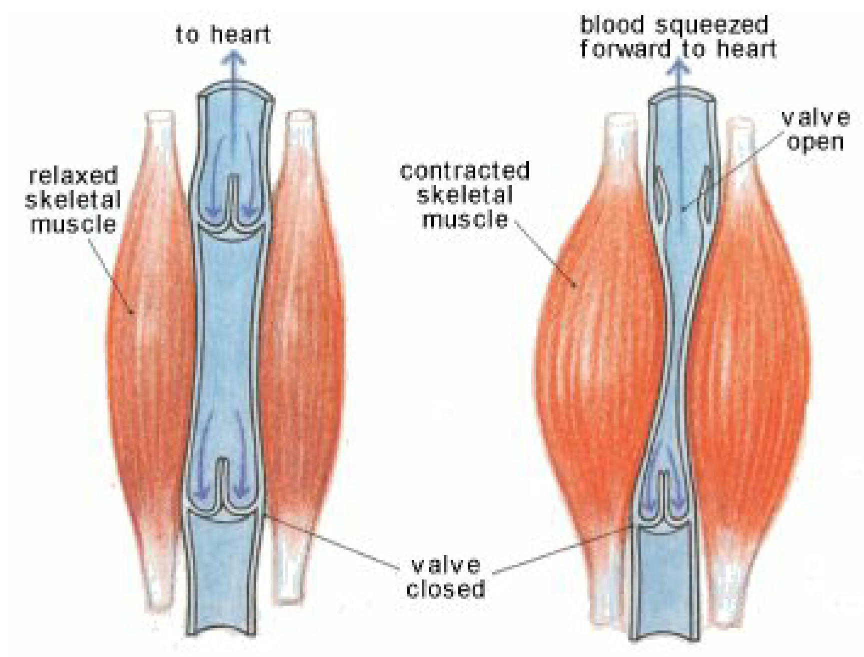


Figure 10. Contraction of skeletal muscles in the legs helps to pump blood toward the heart, but is prevented from pushing blood away from the heart by closure of the venous valves.

Factors That Influence Arterial Blood Pressure

Arterial blood pressure depends on a variety of factors that are at work in the body at any given moment (figure 11). These factors include the pumping action of the heart, blood volume, resistance to flow, and the viscosity (thickness) of the blood. If any of these factors change, the blood pressure will also change so the flow of blood can continue as normally as possible. Let's consider an example in which a person suffers from a cardiovascular disease called arteriosclerosis, where plaque is accumula ting in and clogging the arteries. This example illustrates how resistance to flow can affect blood pressure. As the disease progresses and more plaque accumulates in the blood vessels, the flow of blood faces more and more resistance. In order to maintain an adequate flow of blood, the heart must pump "harder," and therefore the blood that leaves the heart is forced out wi th greater pressure. Thus, the blood pressure is increased. This is a case where the blood pressure is altered and stays altered over a long period of time.

However, an important point to remember is that, when cardiovascular disease is not present, blood pressure very seldom stays altered over a long period of time. This is because the systems that regulate and control your blood pressure are some of the most efficient and fastest regulating systems in the body. Your blood pressure usually increases or decreases in response to some instantaneous need of the body, but then returns back to normal once other regulating mechanisms "kick in." Your body knows how important it is to keep your blood pressure as stable as possible so that appropriate blood flow through the tissues is maintained, particularly in the brain. So, whenever a blood pressure change is detected, the body immediately responds to bring it back to normal. Your body takes good care of your blood pressure. Now, let's look at the factors that can influence a change in blood pressure.

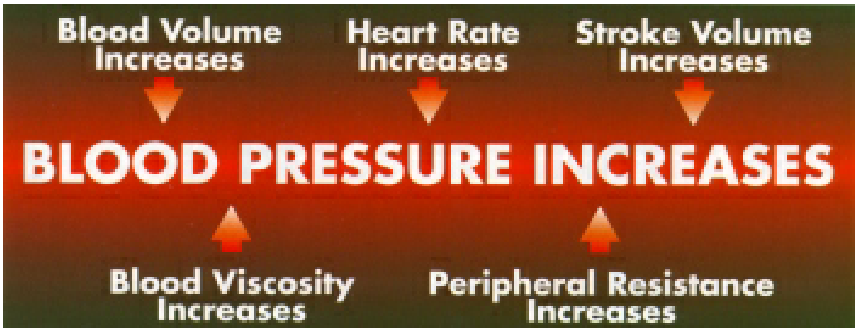


Figure 11. Some factors that influence arterial blood pressure.

The volume of blood discharged from the ventricle with each contraction is called the **stroke volume** and equals about 70 ml for an adult at rest. As stated earlier, the volume of blood discharged from the ventricle (or the heart) per minute is called the **cardiac output**. It is calculated by multiplying the stroke volume by the heart rate in beats per minute.

Formula: Cardiac output = stroke volume x heart rate
Units: ml of blood/minute = ml of blood/beat x beats/minute

The blood pressure in your body usually changes in response to changes in cardiac output. In other words, as the cardiac output increases, so does the blood pressure. If the cardiac output decreases, so does the blood pressure. (Usually, however, blood pressure returns back to normal very quickly. Remember, your body takes good care of your blood pressure.) But what would make the cardiac output increase or decrease? Look at the formula above. If either the stroke volume or the heart rate increases, so does the cardiac output and, as a result, the blood pressure rises. Conversely, if the stroke volume or the heart rate decreases, so do both the cardiac output and the blood pressure.

Friction between the blood and walls of the blood vessels creates a force called **resistance**. This force must be overcome by blood pressure if the blood is to continue flowing. Consequently, factors that alter resistance cause changes in blood pressure. Resistance in the systemic portion of the circulation is called peripheral resistance.

The **viscosity** of a fluid is related to the ease with which its molecules flow past one another. Measurement of viscosity could also be thought of as measuring how thick a fluid is. As viscosity increases, fluids flow less easily. (Think of the ketchup commercial on television where the watery ketchup pours quickly while you wait in anticipation for the other, more viscous ketchup to pour!) Blood cells and plasma proteins increase the viscosity of the blood. This prevents the blood from flowing as easily as water (remember the saying "blood is thicker than water"). Therefore, greater force is needed to propel it through the vascular system. So, it is not surprising that blood pressure rises as blood viscosity increases. Conversely, blood pressure will decrease as blood viscosity decreases.

Central Venous Pressure

We have just examined the arterial blood pressure, which is a measure of the pressure of the blood leaving the heart. Another pressure of great interest is the pressure of the blood entering the heart. All the venous blood (from the veins) of the body drains into the right atrium. The pressure in the large vein (vena cava) just outside the right atrium is called the **central venous pressure (CVP)**. This pressure is of special interest because it provides an indication of the volume of blood that is flowing through the veins and into the right atrium. If the heart is beating weakly, blood tends to "back up"in the veins. The CVP, as a measure of this back-up, will increase. Also, if the blood begins to back up (measured by increased CVP), the heart can respond in two ways: (1) it can beat faster, and (2) it can pump more blood with each beat. When the heart responds in this way, then the back-up is relieved. As the back-up is relieved, the CVP decreases back to normal.

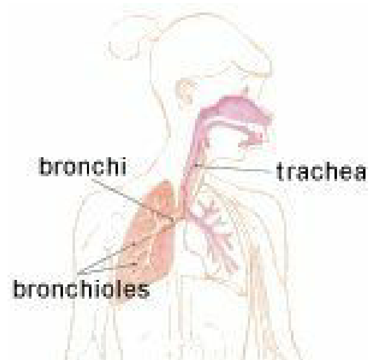
Besides a weakly beating heart, another factor that increases the flow of blood into the right atrium, and thus causes the CVP to become elevated, is an increase in blood volume. This can happen when we go to bed at night, because when we lie down, gravity is no longer pulling the blood "down" in the same way it does when we stand up. Again, the elevated CVP is alleviated by the heart's response to move the blood faster.

Now, let us add to our picture of the heart and blood vessels to understand how oxygen from our atmosphere enters the blood system to "feed" and provide energy for all the activities we carry out every second of our lives. We will examine the gateway through which we take in oxygen and breathe out carbon dioxide: **the respiratory system**.

The Respiratory System

The cardiovascular system cannot carry out its prescribed duties for the body unless the respiratory system contributes its share faithfully. Respiration is the overall process of exchanging oxygen and carbon dioxide between the environment and the blood. **Respiration** may be broken into three stages: (1) the process of breathing, which involves the movement of air into and out of the lungs (the **pulmonary system**); (2) the exchange of gases between the internal surface of the lungs and the blood; and (3) the exchange of gases between the blood and the cells of the body. The combined system with the heart and lungs working together is often called the **cardiopulmonary system** (Figure 12a).

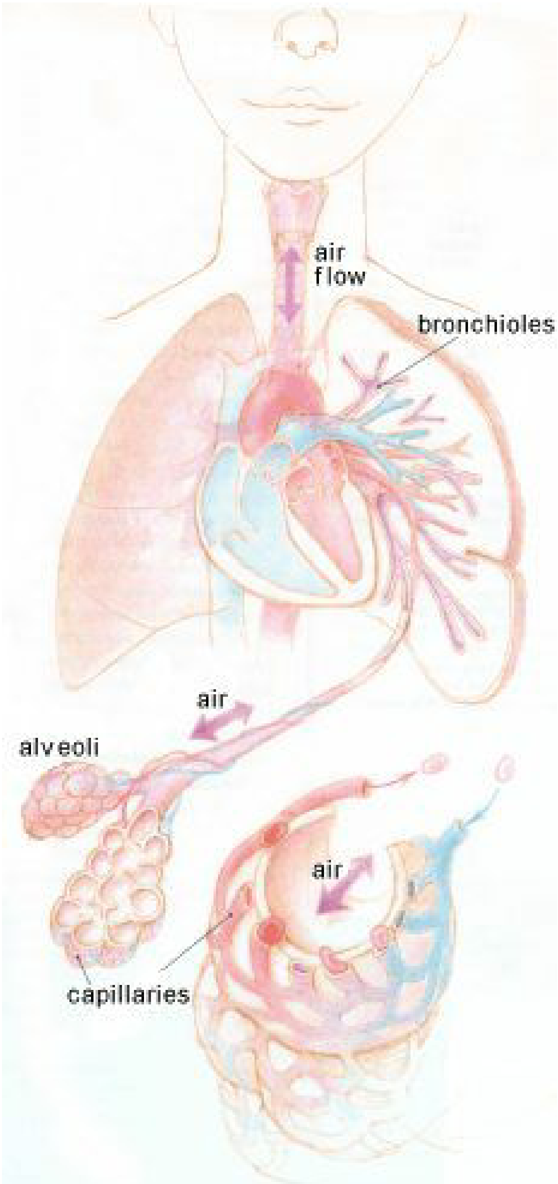
Figure 12a. The respiratory tract through which air enters the cardiopulmonary system.



Movement of air from the external environment into the lungs is accomplished by the action of two groups of muscles. The first is the **diaphragm**, a muscular wall that divides the trunk's body cavity into two parts, the chest and the abdomen. The second consists of the rib muscles (**intercostal muscles**). These muscles act together to change the size of the chest cavity. The rib muscles are attached to your ribs, which in turn encircle the lungs and chest cavity. Together, this system is often referred to as the **rib cage**.

The **respiratory tract** is the pathway for air to enter the body. It is one of only three main gateways that connect the "outside" of the body to the "inside" of the body (the other two are the digestive tract and the urinary tract). The process of respiration involves many interactions. Let us begin with **inspiration** (inhaling). Air is drawn into the lungs as a result of the combined expansion of the rib cage and the lowering of the diaphragm; in normal breathing it is lowered about 1 cm; in heavy breathing it can be lowered up to 10 cm. When the lungs are expanded in this state, atmospheric pressure, the pressure outside the body, is higher than the pressure in the lungs. Air flows from the higher to the lower pressure areas and into the lungs through a system of channels that begins with the **oral cavity** (mouth) and the **nasal cavity** (nose). The air flow then continues through the **trachea** (the windpipe) and into the **bronchi** which are two large tubes, one for each lung. Finally, stemming from the main bronchi are smaller bronchi and tiny **bronchioles**, much like branches and twigs stemming from a tree trunk.

Figure 12b. The exchange of gases occurs between the membranes ofthe alveoli and the surrounding capillaries. The red blood cells are thevehicles that carry the carbon dioxide to and oxygen away from thealveoli.



Arriving at the bronchioles, the air has yet to unload its cargo of oxygen. The start of this task is taken on by vast armies of tiny, expandable, thin-walled, clustering sacs called **alveoli**. There are estimated to be about 300 million of these small air sacs in an average-sized adult. The alveoli constitute the bulk of lung tissue; it is their substance that makes the lungs soft and spongy. When the lungs expand or contract, it is the alveoli that are expanding or contracting. **It is from the alveoli that the blood receives its oxygen.**

Every alveolus in your lungs is covered with capillaries (Figure 12b). Every single red blood cell (RBC) in your bloodstream flows through these pulmonary capillaries so they can pick up an oxygen molecule and give up carbon dioxide. Layers of capillary and alveolar cells lie in direct contact side by side with a double membrane, almost unimaginably thin, with air moving on one side and blood flowing past on the other. The oxygen is soaked into the blood via this virtually transparent wall and snatched up by the **hemoglobin** in the RBCs, where the iron in the hemoglobin locks the oxygen in a chemical embrace. Swept along in the bloodstream, the oxygen finally arrives at the body's waiting cells to unite with the body's fuel and free the energy in them to be used to enable our body to move and function.

The actual quantity of **oxygen uptake** per minute (the rate of oxygen taken in by the cells) during this process may vary from one minute to another, depending on the rate of breathing and the speed with which blood is being pumped through the arteries. This, in turn, depends on how much energy the body requires at the time. Someone snoozing in a hammock may absorb only half a pint of oxygen a minute, while a person running the mile to beat a world's record may soak up more than five quarts in the same period.

The lungs are not only responsible for the delivery of oxygen to the bloodstream. Simultaneously, they draw out of the blood the waste carbon dioxide produced by the utilization and breakdown of carbon compounds (fats and carbohydrates) that provide energy in the cells. The carbon dioxide is picked up from all the cells of the body and carried along by the RBC on its way to obtain oxygen from the lungs. Once inside the lungs, the carbon dioxide is brought alongside the alveolar membrane, where it seeps out of the bloodstream just as the oxygen seeps in. Although the two gases pass through the same membrane, they have absolutely nothing to do with each other. They are like total strangers boarding and leaving a train at a single station. From the lungs, the carbon dioxide makes its way out of the body along the same route the oxygen followed on its way in. This is done during the process of **expiration** (exhaling).

In expiration, the rib cage and the diaphragm relax and the lungs contract (become smaller). During this process, the air pressure inside the lungs is higher than the atmospheric pressure and air is forced out. However, the lungs never completely deflate; that is, some air always stays in the lungs. This volume of air that always stays in the lungs is called **residual volume**. The volume of air that moves in or out of the lungs in one normal breath is called the **tidal volume**. Definitions for other important respiratory measurements are found in Table 1.

Table I. Definitions of respiratory measurements.

Tidal volume	The amount of air that moves in or out in one normal breath (~500 ml.)
Inspiratory reserve volume	The amount of air that can be inhaled beyond the normal indrawn breath (~2900 ml.).
Expiratory reserve volume	The amount of air that can be exhaled beyond the normal exhaled breath (~1100 ml.).
Vital capacity	The amount of air that can be inhaled in the deepest breath and exhaled completely (~4500 ml.). Vital capacity = tidal volume + inspiratory reserve volume + exploratory reserve volume.
Residual volume	The amount of air that cannot be expelled from the lungs no matter how hard one tries (~1200 ml.).
Total lung capacity	The amount of air that can be accommodated by the lungs. Total lung capacity = vital capacity + residual volume

Proper functioning of the cardiopulmonary system is essential for a human being to survive. In fact, the lungs work so closely with the heart and blood vessels that certain heart function measurements can actually be obtained from measurements of pulmonary function. That is, measurements that involve breathing can actually yield information about the blood flow through the heart. For instance, flow rates such as **cardiac output** can be obtained from pulmonary function measurements. This works because all the blood that flows into the lungs to be oxygenated equals the amount of blood that flows out of the heart. That is, the amount of blood flowing into the lung's capillary beds is equal to the amount of blood flowing out of the heart. Blood flow through the lungs is called **pulmonary blood flow (PBF)**. Thus,

cardiac output = PBF

An important technique used to determine cardiac output involves using a sophisticated breath analyzer to analyze the composition of gases in the astronauts' breath. This is similar to the breath analyzer test that the police use to measure alcohol blood content in a person they suspect has been drinking and driving. We will go into this idea more completely later, when we discuss how this technique was used in space to determine cardiac output.

The cardiovascular system and the cardiopulmonary system work together to interact with every cell and organ in the body. The blood vessels serve as the communication line between all the body systems. Therefore, small changes in any of these body systems can have a "waterfall" effect that spreads and creates changes throughout the body. Every moment of our lives, hundreds of thousands of complex interactions take place in our bodies. Over millions of years, the human body has evolved in conjunction with the force of gravity. You have had a glimpse of the complexity of the body's systems down to the microscopic level of the capillaries and the alveoli. What do you suppose happens when an environmental constant like the force of gravity is removed?

Let's move on to our investigations into how space flight affects the heart, lungs, and blood vessels.

Space Physiology

The heart, lungs, and blood vessels function differently in space than they do here on Earth . You already know this by now, but we are going to examine this statement in some detail by focusing on Dr. Blomqvist's investigation, which has already been carried out in space. We will look at some of the space flight data that has been collected in order to understand the **adaptation process** that the body undergoes in space. We will then look at how the body readapts to Earth once the astronauts return.

Scientists have hypothesized that the cardiovascular system begins to adapt to weightlessness as soon as the blood and other body fluids move from the feet, legs, and lower trunk to the upper body, the upper trunk, and the head. This **fluid shift** causes the heart to enlarge, at first, to handle the increased blood flow (Figure 13). Even though the body still contains the same total fluid volume at this point, additional fluids have accumulated in the upper body in a way that doesn't happen of Earth during normal activities. The brain and other body systems interpret this increase in blood and other fluids as a "flood" in the upper body. The body then reacts to correct this situation by getting rid of some of the "excess" body fluid. Astronauts bec ome much less thirsty than normal, and the kidneys, with the help of the endocrine system (which produces and delivers biochemical messengers, hormones, throughout the body), increase the output of urine. Both actions decrease the overall quantity of fluids and electrolytes (ions such as sodium and potassium) in the body, and lead to a reduction in total circulating blood volume. Recall that the heart enlarged somewhat when more blood moved into the upper body. Now, however, once the fluid levels are decreased and the heart does not have to word against gravity, the heart shrinks somewhat in size.

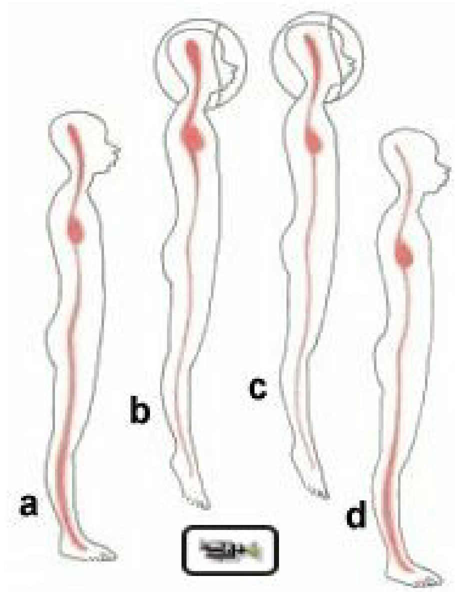


Figure 13. The fluid shift phenomena of space flight. (a) On Earth, gravity exerts a downward force to keep fluids flowing to the lower body. (b) In space, the fluid tends to redistribute toward the chest and upper body. At this point, the body detects a "flood" in and around the heart. (c) The body rids itself of this perceived "excess" fluid. The body functions with less fluid and the heart becomes smaller. (d) Upon return to Earth, gravity again pulls the fluid downward, but there is not enough fluid to function normally on Earth.

Why is it important to understand the changes that occur in the functioning of the cardiovascular system in space? There are a number of answers to that question. First, we want to be certain that astronauts remain healthy in space, and that they will continue to lead normal lives after they return to Earth. That is, we want to know whether the changes that occur in the functioning of the human body in space are **reversible**. Second, we want the astronauts to be comfortable in space, and we want to be certain that they can perform their important duties on each space flight mission. In fact, we want to do everything possible to ensure the success of the missions that thousands of people have worked so hard to make possible. Third, this type of research has important implications for people on Earth. You yourself may have experienced dizziness or a fainting feeling when you have stood up too quickly. This momentary sensation is the result of the rapid shift of about a pint of body fluid. However, some people suffer from fainting or dizziness spells with no apparent cause. Any research directed at obtaining a basic understanding of how the cardiovascular system works can help medical doctors and their patients cope with many types of cardiovascular problems on Earth.

A comprehensive cardiovascular investigation developed by Dr. Gunnar Blomqvist and his research team was designed to examine the cardiovascular consequences of the fluid shift that occurs during space flight in order to determine how the operation of the cardiovascular system is changed in space when astronauts are at rest and when they are exercising. This investigation measured central venous pressure, arterial pressure, heart rate, and the size of the heart. The investigators also examined cardiac output during exercise and at rest, and leg volume changes at various times during a mission.

Before we begin our examination of the results from Dr. Blomqvist's study, let's review the original hypotheses that served as the foundation for the development of Dr. Blomqvist's space flight study. In addition, we will participate in some hands-on activities (called Student Investigations) that were designed to provide you with some practical experience with important concepts before you are presented with the actual space flight results.

A **scientific hypothesis** is a simple, direct statement about what the experiment is designed to examine. You have probably learned that a hypothesis is an "educated guess." This is true, and if the experiment is well designed, the results will either agree with the hypothesis (and therefore support it), or the results will disagree with the hypothesis (and therefore refute it). Dr. Blomqvist's investigation is designed to support or refute two simple scientific hypotheses:

Hypothesis 1
Adaptation of the heart and cardiovascular system to microgravity is rapid and effective. The adaptation is primarily a general response to a head ward shift of body fluids.

Hypothesis 2
Upon reentry to the Earth's atmosphere and the return to normal gravity, the cardiovascular problems (dysfunction) experienced by the human body are a result of the body having adapted to a space-normal condition. This spacenormal condition is challenged by the sudden return to normal gravity.

Your Perspective

Before describing some of the actual experimental procedures that Dr. Blomqvist and his team carried out, and before we present to you the results of those experiments, it is important for you to experience directly (through a **simulation**) some of the physiological changes that astronauts experience in space. In this section, you will carry out three experiments related to the effect of fluid shift on cardiovascular function. These experiments will build your experience progressively, ultimately producing effects similar to those experienced by astronauts during space flight. You should imagine that you are a scientist with an experiment scheduled on an upcoming shuttle flight, and you are carrying out groundbased studies to obtain data similar to that expected from your space flight experiment. In general, such groundbased studies are an important aspect of any physiology experiment in space, because they help the scientist sort out details of his/her experiment before flight.

Many of the experiments carried out as a part of the space program are complex and require a lot of teamwork. In order to carry out the following studies properly, you will need a team of your own. Break into small groups to discuss the approach your team will use to carry out each phase of the three experiments, including the design phase, the measurement phase, and the analysis phase. Remember, these three experiments build on each other progressively, so it is important to discuss the approach to all three investigations before you begin the first one.

In what follows, you will be provided with adequate background information for each experiment, but it is important that you understand that you are expected to design the actual experiments. Designing an experiment is not difficult once you understand the general steps used. Here is one set of steps that will lead to an experiment design. You have probably been exposed to this set of steps before under another name: **the scientific method**.

The Scientific Method

1. Hypothesis Development

The first step in designing an experiment is to develop a scientific hypothesis. The hypothesis should be a simple statement of what you expect to be true, or what you expect to learn, about the particular phenomena you are studying. That is, the hypothesis is your prediction about what an experiment will teach us. In this particular exercise, hypotheses will be provided for the first two investigations, but it will be up to you to develop an appropriate hypothesis for the last one.

2. Protocol Development

Next, you should design the actual steps that you will use to determine whether the hypothesis is true. The **protocol** is simply the method used to obtain the measurements you will make. The protocol should be written down in a step by-step fashion. In designing your protocol, be aware of the need to make a set of measurements that represents a normal condition with which you will compare other measurements. Such normal measurements are known as the **control** (**baseline**) set of measurements. It is from a comparison of your experimental measurements with your control set of measurements that a change can be detected and a conclusion can be reached.

3. Data Collection

By carrying out the protocol as you have defined it, you will make the appropriate measurements. In other words, you will collect the data. You should record this data in an organized fashion. Keeping track of the data is one of the most important, and sometimes one of the most difficult, parts of carrying out an experiment.**Stay organized.** Again, remember to record a control set of measurements under normal conditions before you begin making measurements of the altered condition required by your protocol.

4. Data Analysis

Now, it is time to analyze the data. The objective of this step is to take the data you have collected and put it in a form that ultimately lets you draw a conclusion about the hypothesis you have selected. It may be that you must use your measurements (raw data) in some kind of mathematical equation to calculate the needed final data that supports or refutes your hypothesis. It may be that you must prepare a graph of your measurements to show certain relationships clearly or to exhibit trends that are present in the data.

5. Data Interpretation

Finally, it is time to interpret the data. Does the data you obtained support or refute your original hypothesis? This step is the telling step. It seems that we would always want to have results that support our hypothesis, but sometimes we obtain results that tell us that we are completely wrong about our prediction or hypothesis. Having a hypothesis that is not supported by the data can sometimes teach us more and help us develop a better experiment for the next time.

Let's move on to the Student Investigations!

Student Investigation 1

Demonstration of How Cardiac Output and Exercise Are Related

Background

Cardiac output is the amount of blood pumped by the heart in a unit of time. Usually it is measured in liters/minute (L/min). Cardiac output is a fundamental indicator of how the health of the heart and cardiovascular system. On Earth and in space, different conditions can influence cardiac output. For instance, if a person is exercising heavily, the body requires more oxygen to fuel the muscles. Therefore, the heart pumps harder (increasing cardiac output) so that the blood flow to the muscles can increase and the needed oxygen can be provided more rapidly by the blood. The opposite occurs with a person who is bedridden and requires less oxygen for the muscles, so cardiac output is decreased.

Cardiac output can change in response to different needs of the body. Because it can change, it is called a **variable**. In a normal adult human at rest, the cardiac output is about 5 L/min. Two other variables that contribute to the cardiac output are stroke volume and heart rate. Stroke volume is the amount of blood pushed through the heart during each heart beat. It is usually measured in milliliters per beat (ml/beat). Stroke volume normally remains relatively stable at about 75 ml/beat. The heartrate defines how fast the heart is beating. It is measured by taking one's pulse, and it is usually measured in beats per minute (beats/min). The product of the stroke volume and the heart rate is equal to the cardiac output, or

$$\underset{\text{(ml/min)}}{\textbf{Cardiac output}} = \underset{\text{(ml/beat)}}{\textbf{stroke volume}} \times \underset{\text{(beats/min)}}{\textbf{heart rate}}$$

Investigation 2.1 is designed to familiarize you with how exercise affects cardiac output here on Earth. Later, you will have an opportunity to use the experience you gain through this investigation to help you develop and test a hypothesis about how exercise affects cardiac output in space.

Hypothesis

Design your experiment around the following hypothesis:

On Earth, an increase in normal activity by a human being results in an increase in cardiac output.

This means that as a person increases his/her level of exercise, his/her cardiac output increases also. Note that this hypothesis says nothing about how much or when the cardiac output increases. It is important to simplify any hypothesis as much as possible, so that you can answer one question at a time.

Protocol Development

Materials

Watch or clock with a second hand

Procedure

The requirements to carry out this investigation are:

- You must make more than one set of measurements.
- Remember to be consistent in your measurements.

Keep in mind that the Background section of this investigation provides information that will serve as a guide for you as you design your experiment. Remember, you are attempting, through your experimental design, to gather data that will support or refute the hypothesis.

Data Collection, Analysis, and Interpretation

Table 2. Cardiovascular data sheet.

CARDIOVASCULAR DATA SHEET

Record the subject's (your) heart rate:		beats/min
Assume the subject's (your)stroke volumes is 75 ml/beat.		
Calculate the subject's (your) resting cardiac output:		ml/min
	=	L/min
Record the subject's (your) heart rate after exercise:		beats/min
Calculate the subject's (your) cardiac output after exercise:		ml/min
	=	L/min

Write down the hypothesis:

The results of this investigation is that my hypothesis is (correct or not correct):

Questions

1. Explain any differences you detected in cardiac output before and immediately after exercise. Give a reason for such a difference.
2. A class similar to yours measured cardiac output at rest on Subject #1 and then they measured cardiac output after exercise on Subject #2 (two different people). Subsequently, they stated that their data supports the hypothesis for this investigation. What is wrong with their conclusion?
3. If Subject #1, Subject #2, and Subject #3 performed the same exercise for the same amount of time, would the measured increase in cardiac output for all three be exactly the same? Give a reason for your answer.

Student Investigation 2

Can the "Puffy-Head, Bird-Legs" Syndrome be Simulated in a High School Classroom on Earth?

Figure 15. These pictures show the "Puffy-Head" Syndrome, with the astronaut's face before and after space flight.

Background

All astronauts, when they leave the constant gravity field of Earth, experience the phenomenon known as the "Puffy-Head, Bird-Legs" Syndrome. The astronauts report a "stuffiness" of the sinuses, together with a feeling of "fullness" in the head, and "puffiness" of the face {Figure 15). Also, measurements taken before space flight, during space flight, and just following space flight have shown that the legs do change their shape inflight (Figure 16); they decrease in volume and actually look skinnier compared to the preflight leg shape. Astronauts have termed this curious condition "bird legs." after space flight, measurements show that the legs return to a normal shape. These reported sensations in the head and measured changes in the legs support the hypothesis of substantial headward fluid shies inflight.

Figure 16. Inflight measurement of leg circumference.

It is interesting that measurements of leg circumference taken in space on those astronauts with larger legs show a proportionally larger decrease in leg volume than those with smaller legs. This is explained by the fact that the more muscle a person has in his limbs, the more fluid and blood flow is required to "feed" those muscles. The more fluid and blood there is, the more there is to lose. Another interesting and important fact to keep in mind about space flight is that the fluid shift actually begins on the launch pad, because the astronaut is seated in the space shuttle in a reclining position with his/her legs elevated, sometimes for several hours prior to launch (Figure 14).

Figure 14. Astronauts awaiting launch are in a reclining position with their legs elevated. Launch delays can sometimes last up to three or four hours.

To simulate the head ward shift of body fluids here on Earth, scientists use the bed rest head-down tilt method. In this "model," subjects are recruited to stay lying down in a bed that is tilted five degrees down from the horizontal at the head, while the legs are elevated five degrees above the horizontal. Some studies of this type last only 24 hours, but

others have lasted up to about a year.

An interesting point to make here is that during the early portions of this head-down tilt orientation, a subject's stroke volume increases from about 75 mL/beat to about 90 mL/beat. This is entirely expected, because there is a rush of fluids to the upper part of the body and the heart then has more blood to force out during each beat. In addition, to compensate for this increase in stroke volume (to keep cardiac output relatively stable), the subject's heart rate decreases. Therefore, during the portion of this Student Investigation where you are determining cardiac output, don't be surprised when you obtain lower values for the subject's heart rate. This is normal.

Hypothesis
Design your experiment around the following hypothesis:

A head-down tilt orientation to the human body will induce physical characteristics that indicate a shift of fluids toward the upper part of the body.

This means that if a human being is oriented or tilted with his or her head below the horizontal and his or her legs above the horizontal, physical characteristics will appear that indicate a shift of fluids toward the upper part of the body.

Protocol Development

Materials
Ruler and piece of string or a tape measure
Pillows and a chair (optional)
Watch or clock with a second hand

Procedure
The requirements to carry out this investigation are:

- In the leg volume determination you must make more than one measurement. Always measure the leg the same each time. (Remember your control measurement.)
- Measure leg size on the lower part of the leg (calf) at the same place each time you do it.
- Write down the hypothesis, along with your procedures and results. You will need them later.
- Make a determination of cardiac output on your head-down tilt subject(s). This will represent a resting cardiac output measurement under the conditions of an induced head ward fluid shift (Remember to use the value of 90 mL/beat for stroke volume in your calculation of cardiac output.) This data can be used later for Investigation 3.

Data Collection, Analysis, and Interpretation

Table 3. Puffy-Head, Bird-legs data sheet.

PUFFY-HEAD, BIRD-LEG DATA SHEET

Write down your observations of the changes in the subject's facial characteristics following orientation of the subject in the head-down tilt position:

Write down the subject's own sensations related to head fullness in the head-down tilt position.

Record your measurement of the circumference of the leg in an upright position.

Record your measurement of the circumference of the leg in the head-down tilt position.

Resting cardiac output in the head-down tilt position:

Heart Rate	=		beats/min
Cardiac Output	=		mL/min

Write down the hypothesis:

The results of this investigation is that my hypothesis is (correct or not correct):

Questions

1. What is the main factor responsible for the head ward fluid shift that occurs both in space and, using the head-down tilt simulation, on Earth?
2. The Moon has one-sixth the amount of gravity that the Earth has, and Mars has one-third the amount of gravity that the Earth has. On which of the two, the Moon or Mars, would you experience a greater head ward shift of fluid compared with your normal condition on Earth? Why?
3. Compare your calculated results of the resting cardiac output for the same subject under conditions of standing upright and under conditions of head-down tilt. Does a head-down tilt orientation affect the total value for cardiac output? With your knowledge about how the head-down tilt orientation affects stroke volume and heart rate, explain your answer.

Student Investigation 3

Does the Headward Fluid Shift Affect Cardiac Output During Periods of Exercise?

Investigation 1 helped you become familiar with the concept of cardiac output and the effects of exercise on cardiac output. To carry out this investigation, you made a determination of and compared (1) resting cardiac output to serve as your control, and (2) cardiac output under conditions of exercise. Investigation 2 helped you become familiar with the head ward fluid shift that astronauts actually experience during space flight. Not only did you become familiar with the physical symptoms of the head ward fluid shift phenomenon, but you made a determination of cardiac output for your headdown tilt subject while he/she remained at rest. This led you to become familiar with how the head ward fluid shift affects stroke volume and heart rate. The present investigation will tie these two studies together by looking at the influence of head ward fluid shifts on cardiac output during periods of exercise.

Hypothesis
Develop your own hypothesis for this particular investigation. Remember to keep it simple and direct. Use the hypotheses from Investigations 1 and 2 as models.

Protocol Development

Materials
Ruler and a piece of string or tape measure
Watch or clock with a second hand
Pillows and a chair (optional)

Procedure
The requirements to carry out this investigation are:

- Your hypothesis must specify human beings as the subject of the investigation.
- You must take more than one set of measurements. (Remember your control measurements.) Also, if you use the same subject, you may use results of the two previous investigations.
- Design your experiment to support or refute the hypothesis.

Data Collection, Analysis, and Interpretation

Table 4. Exercise data sheet

Exercise Data Sheet

Upright position:

Calculate and record resting cardiac output: l/min

Calculate and record cardiac output after exercise: l/min

Head-down tilt position:

Calculate and record resting, cardiac output: l/min

Calculate and record cardiac output after exercise: l/min

How did you verify that a headward fluid shift did occur before taking heart rate measurements? Record your observations.

Write down your hypothesis:

The results of this investigation is that my hypothesis is (correct or not correct):

Questions

1. Why do you think a head ward fluid shift combined with exercise affects cardiac output?

2. Why is it important not to compare data taken from one subject with data taken by different measurements from another subject?

Conclusions of Student Investigations 1 - 3

The experiments that you have just completed have given you added insight into how your cardiovascular system responds to exercise and to a simulated fluid shift. In particular, you have sharpened your understanding of how stroke volume, heart rate, and cardiac output are related. As you will see, your involvement in these exercises will help you better understand Dr. Blomqvist's space flight investigation.

Next, you will be involved in two investigations that will help you understand the pulmonary system. By the time you finish these exercises, you will have further prepared yourself to venture into the excitement of Dr. Blomqvist's space flight investigation. The two exercises were designed to provide you with background about the basic respiratory measurement techniques that are widely used to determine pulmonary function status. They are the starting point for understanding the pulmonary physiology of your body. You should read through both exercises before beginning the first one.

Let's begin our next set of Student Investigations!

Student Investigation 4

Defining and Graphically Interpreting Respiratory Measurements

Background
At the beginning of this Case Study, you were introduced to the concept of respiration. There are four measurable respiratory volumes that are important indicators of respiratory fitness: (1) **tidal volume (TV)**, (2) **inspiratory reserve volume (IRV)**, (3) **expiratory reserve volume (ERV)**, and (4) **vital capacity (VC)**. (The term capacity is used to refer to a volume that is obtained by adding together two or more other volumes.) The **residual volume (RV)** is not an easily measured value, but there is an accepted standard value attached to this volume that can be used when needed for calculations or graphing exercises. From these measurements, one can obtain, through calculation, the **total lung capacity (TLC)**. A table of definitions for these respiratory measurements was presented and explained to you earlier in this Case Study; you will find that table reproduced here for your convenience.

You will be instructed to obtain your personal respiratory measurements in the next Student Investigation. Before we move forward to that step, however, it is important to be able to graphically interpret the respiratory measurement definitions that you have already become familiar with.

Procedure
Each student should carry out this exercise independently. Your teacher will provide a separate handout for you to complete. Examine the respiratory measurement definitions in Table 1 in the Earth Physiology section and use those definitions to fill in the blanks on the graph in Figure 17.

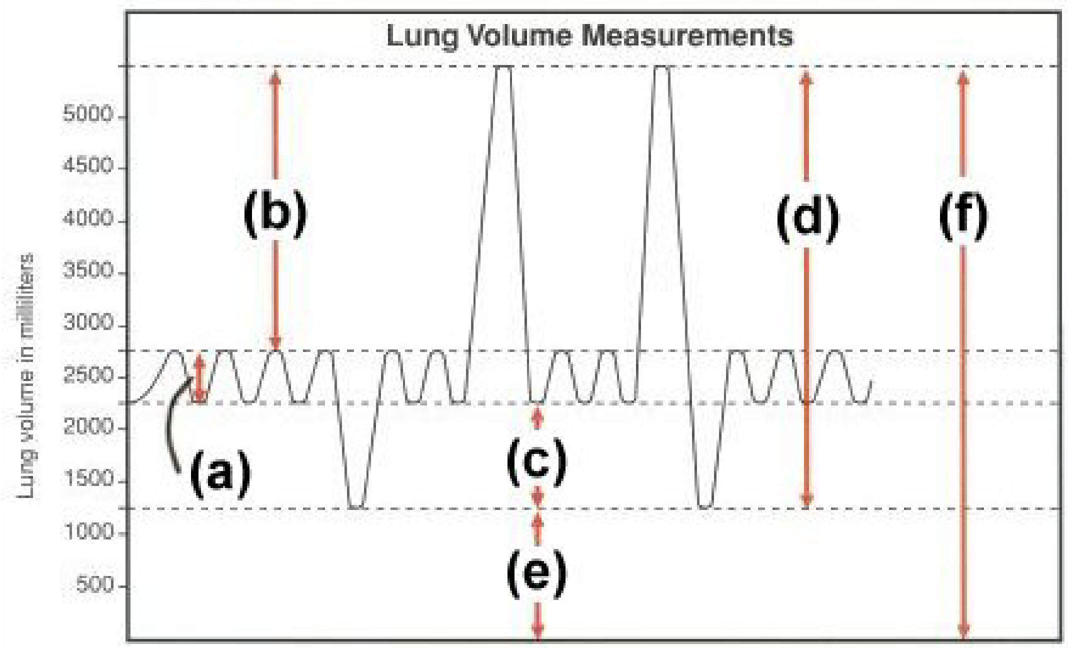


Figure 17. Lung volume measurements. Using the definitions in Table 1

Student Investigation 5

Determination of Your Personal Respiratory Measurement Profile

Background
The exchange of gases at the cellular level depends mainly on the integrated functioning of the cardiovascular and respiratory systems. Proper delivery of fresh air to the circulating blood and control of this delivery are examined in assessing respiratory functions.

The special tests to examine the volume of air in the lung during various respiratory maneuvers and to determine the rates of air flow are known as **pulmonary function tests**. Applying these tests to a subject and comparing his or her individual measurements with known standards allows certain patterns of impaired (improper functioning) lung function to be revealed. In the case of space flight, changes in lung function detected through inflight experimentation are not expected to suggest an impairment of function, but should be indicative of a readaptation of the system to its environment. We expect this to be the case because each astronaut has participated in preflight baseline control studies to characterize his or her respiratory profile (documentation of the astronaut's personal respiratory behavior), and has been found to be normal. (If the astronaut had exhibited impaired respiratory function in these preflight studies, he or she would have been removed from flight status.) Then, on theoretical grounds, it is expected that space flight will improve, not degrade, the respiratory profile.

Pulmonary function tests can examine either the **static** (**volumes** or **capacities**) or the **dynamic** (**rates of change** or **volumes per minute**) characteristics of the pulmonary system. The volume of air that moves in and out of the lungs during breathing is measured with an apparatus called a spirometer. You will be using a **spirometer** to measure and characterize your own respiratory profile. You will be plotting the results of this investigation on graph paper to produce a curve that is similar to the graph that you worked on in the previous exercise.

Not all the graphs generated by the students in your class will be exactly the same. It is important to note that the individual variability of the respiratory measurement, and, consequently, each student's graph is a result of many factors, including differences in the level of aerobic fitness, age, sex, height, and weight of each individual student in the class. The average values for the respiratory measurements shown in Table 2 serve only as general estimates for the normal volume determinations.

Materials
Spirometer with disposable mouthpieces
70% alcohol and cotton balls
Graph paper

Procedure
1. Students should work in pairs. All students should carefully follow the protocol described below for using the spirometer.

2. To obtain data for the graphing exercise, three measurements will be made: tidal volume (TV), expiratory reserve volume (ERV), and vital capacity (VC). The inspiratory reserve volume (IRV) will be calculated using the known relationship between VC, TV, ERV, and IRV. (It is left up to the student to determine the equation for obtaining IRV.) In addition, total lung capacity (TLC) will be calculated using the known relationship between VC and residual volume (RV). The RV value to be used in this calculat ion and in the graphing exercise should be the accepted general value of 1200 ml.

Protocol for Using a Spirometer

1. Each student should use his/her own sterile mouthpiece. Always sterilize the stem of the spirometer with a cotton ball dipped in alcohol before attaching a new mouthpiece.
2. The amount of air that moves in and out of your lungs during normal breathing is called your tidal volume (TV).
   To determine your TV:
   a. Set the spirometer dial to 0.
   b. Breathe normally for 30 seconds.
   c. Put the spirometer mouthpiece attached to the spirometer into your mouth.
   d. Inhale through your nose and exhale through the spirometer three times, breathing normally.
   e. The spirometer reading shows the total volume of air in your three breaths. Divide by 3 to obtain the

value for your TV. Record that value.

3. Take a normal breath in and out (TV) and hold it for two seconds. Now continue to breathe out and expel as much air as possible. This is your ERV. It is the amount of air you can continue to expire a her the tidal volume.
   To determine your ERV:
   a. Set the spirometer dial to 1000 ml.
   b. Breathe normally for 30 seconds.
   c. after exhaling normally, put the spirometer mouthpiece, which is attached to the spirometer, into your mouth and continue to exhale, forcing all the air possible out of your lungs.
   d. Take the spirometer out of your mouth and breathe normally.
   e. Subtract 1000 from the spirometer reading to obtain the value for your ERV.
   f. Repeat steps (a) through (e) two more times; the highest number is your ERV.

4. The VC is the total amount of air that can move in and out of your lungs. It can be calculated by using the following equation: VC = TV + ERV + IRV. For this investigation, you will measure this value.
   To determine your VC:
   a. Set the spirometer dial to 0.
   b. Take two deep breaths and exhale completely.
   c. Put the spirometer mouthpiece, which is attached to the spirometer, into your mouth.
   d. Inhale as deeply as possible through your nose and exhale as completely as possible through the spirometer at a slow, even pace.
   e. Record the spirometer reading and take a minute or two to recover your normal breathing.
   f. Repeat steps (a) through (e) two more times; the highest value is your VC.

Data Collection, Analysis, and Interpretation
Do not write in your book. Your teacher will provide a copy of Table 5 to record your pulmonary measurements.

Table 5. Personal respiratory profile data sheet.

PERSONAL RESPIRATORY PROFILE DATA SHEET

1. Record the spirometer values for the following respiratory measurements:

TV =

ERV =

VC =

2. Do the necessary calculations to obtain the following values [RV = 1200 ml]:

Inspiratory Reserve Volume =

Total Lung Capacity =

3. Produce a graph similar to Figure 17 using the values obtained above. Compare your graph to Figure 17.

Questions

1. In comparing your graph with the graph in Figure 17, let's imagine that there are tremendous differences in relative values for the various respiratory volumes. How would you explain these differences

2. In the Background section of this Student Investigation, it was stated that "...on theoretical grounds, it is expected that space flight will improve, not degrade, the respiratory profile." Explain why you think this statement is reasonable or unreasonable.

The Space Flight Investigations

Recall that the space flight investigation developed by Dr. Blomqvist was designed to examine the cardiovascular consequences of the fluid shift occurs during space flight. This investigation examines what happens to the cardiovascular system during space flight by studying changes in cardiovascular function, heart size, and the cardiac response to exercise. In addition, and equally important, the same measurements are made on the astronauts before they go into space (preflight), while they are sitting on the launch pad, and after they have been in space and have returned to Earth (postflight).

The **preflight** measurements are essential to understand the "Earth-normal" condition of the astronaut. The **inflight** measurements are taken at different points during the mission and will indicate how quickly or slowly the astronaut's cardiovascular system changes in space. The **postflight** experiments will reveal how the cardiovascular system has become "weaker" compared with how our body functions on Earth. During the postflight sessions, a **stand test** is administered to the astronauts to see how well their cardiovascular system supports them in a standing position. Standing up may not seem, at first thought, to be a difficult thing for astronauts to do. However, it is well known that astronauts are usually not able to tolerate prolonged standing immediately after landing. At this time the experience **orthostatic intolerance** (orthostatic = standing upright, intolerance = unable to handle), characterized by a tendency to faint upon standing. Various cardiovascular measurements are taken to understand the orthostatic intolerance phenomenon more completely.

The preflight, inflight, and postflight portions of this experiment were done on two space missions and the results are very interesting. We will review each major measurement set to see the changes in preflight, inflight, and postflight conditions of the body. For each measurement set, we will include information about **why the measurements are important**, the **equipment used** to make measurements, the expected results, and the **actual results**. These measurement sets were designed to study changes in (1) central venous pressure, (2) heart chamber size, (3) static leg volume, (4) cardiovascular function during a stand test to examine postflight orthostatic intolerance, and (5) cardiovascular function during exercise to examine inflight changes in exercise capacity.

All the results that you will see involve real experimental data. They were actually obtained during the course of preparing for, during, and after the flight of one or more space flight missions. In other words, you are being exposed to the real stuff! Audiences around the world (both scientific audiences and audiences who are not involved in science but who are excited by space flight) have been exposed to this same data and their imaginations have been ignited. Just think, this kind of thing was only in our grandparents' imagination! It is truly now in our reality. However, **all this information and knowledge is worthless unless we are able to communicate and share it with the rest of the world**. One of the most important parts of being a scientist is being able to present the results of an experiment clearly to other scientists, to students, and to all of us, so that we can learn from it and so that we can help science move forward to new and better ideas and questions.

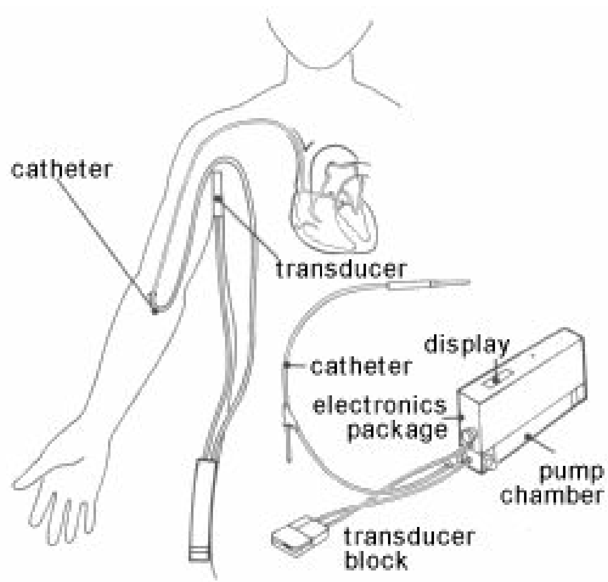
After you review the scientific results presented in each of the next five sections, you will be asked to break into small teams to work on the development of a presentation that members of your team will deliver to your classmates. This activity will be called **"Speaking of Space."** Each small team will take one of the five sections and develop a plan for presenting the information in a clear and concise way. More directions for this activity will be provided later, but for now, let's look at the actual results of the five different experiment sets from Dr. Blomqvist's space flight experiment.

I. Central Venous Pressure

The determination of the central venous pressure (CVP) provides a direct measurement of the changes in the pressure of blood returning to the heart, since the CVP is the pressure in the large vein just outside the right atrium of the heart. Before this experiment was carried out, it was widely believed that this measurement of CVP would establish the amount of fluids that redistribute or shift to the upper part of the body and how rapidly that shift of fluids occurs. As fluids shift toward the upper body, pressure in the veins close to the heart should increase, and this should lead to increased central pressure. As upper-body fluid flow stabilizes or decreases, then this should be reflected directly by a stabilization or decrease in the CVP value. This section will examine if, in fact, these suppositions were correct.

The system for the measurement of CVP provides a means for directly measuring the pressure in the large veins near the heart. Before a mission, a medical doctor inserts a **catheter** (a thin, soft plastic tube) into an arm vein and advances the tube through the veins to a point just outside of the right atrial chamber of the heart (Figure 18). The position of the catheter in the body is verified by taking an X-ray. The catheter is attached to monitoring systems outside of the body that measure and record the changes in CVP. Let's look a little closer at how the CVP system works.

Figure 18. To measure central venous pressure (CVP), a catheter is used.



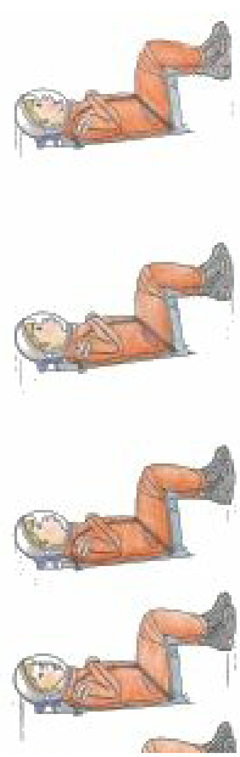
In order to keep the catheter tubing open, a solution of salt water and heparin is pumped continuously through the tubing. Heparin is a substance that stops the blood from clotting; this is important because clotting would cause the catheter to clog. The catheter is directly attached to a CVP recording unit that is strapped to the astronaut's hip. A transducer is placed under the arm of the astronaut at the same level as the catheter tip placement at the opening of the heart.

The actual pressure that is detected by the tip of the catheter travels through the fluid in the catheter line to the transducer. When the pressure reaches the transducer, it is transformed into a proportional voltage signal that is fed to the CVP recording unit. The transducer is not directly attached to the catheter tubing because the salt water in the catheter would conduct the electricity from the transducer right into the body. This would cause the electrical activity of the heart to go completely crazy, endangering the astronaut. Therefore, the transducer and the catheter are kept absolutely separate.

The CVP system also provides an electrical signal to the **physiological monitoring system (PMS)** and the CVP measurement is recorded on the **cassette dote tape recorder (CDTR)**, which is inside the PMS (Figure 19). The function of the PMS itself is to acquire blood pressure and heart rate information from the astronaut at the same time that it is collecting and recording the CVP measurements. The PMS consists of an automatic arm cuff to measure arterial blood pressure, chest electrodes to acquire heart rate information from a recording of the electrical signals of the heart called an **electroccardiogrom (EGG)**, and electronics to process the blood pressure and heart rate data. The PMS is used to gather continuous heart rate data and periodic blood pressure data for as long as the CVP catheter is in place. The PMS displays the data on a numerical display unit, records the data on the CDTR, and has the capability to transfer information to the experiment microcomputer onboard the spacecraft for **downlinking** to groundbased systems back on Earth. The term "downlink" refers to the transmission of data from space via satellite communications to **Mission Control** and thus to the scientists following the experiment on Earth. For Dr. Blomqvist, this afforded him the opportunity to receive the data while the experiment was taking place in space, so he could make sure that the experiment was proceeding smoothly or determine whether any changes in the protocol were needed at any given moment.

Figure 19. The physiological monitoring system (PMS) acquires blood pressure and heart rate information while collecting central venous pressure signals. The astronuats operate the system themselves.

As stated above, investigators believed that the degree and speed of fluid redistribution in the body could be determined by observing the changes in CVP. The CVP system records pressure measurements for the entire shuttle launch sequence while waiting on the launch pad, during the actual launch, and up to about 24 hours while actually in space. After about 24 hours in space, the astronaut removes the catheter by slowly pulling it out of the arm vein. Later, on the day the shuttle returns to Earth and just following the space flight, a medical doctor inserts another catheter back into the arm vein in order to measure the CVP changes associated with the body's **readaptation** to the normal gravity of Earth.



CVP measurements were made by Dr. Blomqvist's team on three crew members. The CVP responses of all three crew members were essentially the same. The fact that the **same results** were observed in **all three astronauts** gives Dr. Blomqvist's team some very strong results that can be "trusted." One of the "hallmark" features of a good science experiment is that the results of the experiment should be **reproducible**. That is, the scientist should be able to obtain the same results over and over again in order to be able to "trust" the results. However, these strong results contradicted some of what researchers believed should happen to the CVP in space. That is, when the astronauts were on the launch pad waiting for their journey to begin, and during the actual launch, the CVP responded exactly as expected. However, when the astronauts arrived in space, the CVP responded in an fashion to what was predicted by Dr. Blomqvist and his team. Let's find out what happened.

Dr. Blomqvist and his team expected the CVP to increase as the astronauts waited on the launch pad. This is because the astronaut is oriented in a supine position (on his back) with his feet elevated and head tilted somewhat downward (Figure 20). It was predicted that the fluids would begin to shift away from the feet and toward the heart area. This should cause the CVP, the pressure just outside of the right atrium, to rise because of the rush of fluids to that area. **This part of the prediction came true for all three astronauts.**

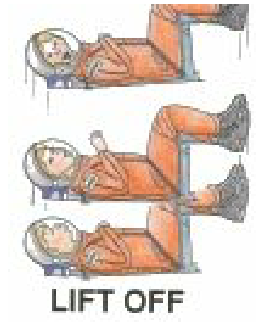


Figure 20. Astronaut orientation during launch.

Then, it was predicted that the CVP would increase even more during the actual launch phase. During launch (Figure 21), the forces that are experienced by the astronauts are equivalent to about three times gravity (or 3 g). Since the astronauts are in a supine position, the direction of this great force is front to back, compressing the chest area. The effect of this force is the same as if a large person were sitting on your chest as you are lying down. It was believed that the result of this mechanical compression force would be to increase the CVP. This part of the prediction also came true for all three astronauts.

Finally, it was predicted that the CVP would remain elevated when the astronaut arrived in space because, as we've already learned, the fluid shift to the head would continue due to the nearly complete absence of gravity. **This part of the prediction did not come true for any of the three astronauts.** Let's discuss specifically what happened by examining an analog tracing of the CVP response that was obtained for one of the astronauts (Figure 22).

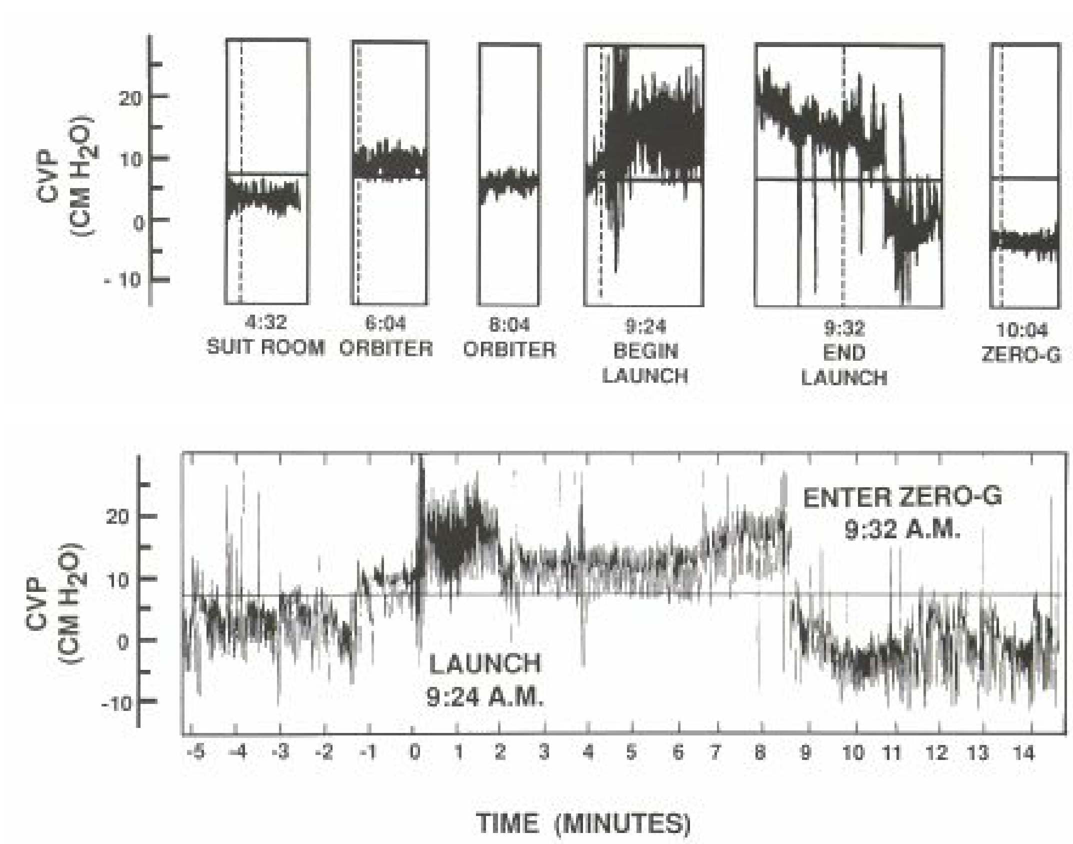


Figure 22. Analog tracing of the central venous pressure response to various phases of the mission including the preflight control measurement, sitting on the hunch pad, during the actual launch phase, and immediately upon entering the virtually gravity-free environment of space. The reference to "zero-G" in the figure acually refers to microgravity.

First of all, and as expected, the CVP was found to increase while the astronauts waited in the launch position. Secondly, as expected, the CVP increased further during the high-g forces experienced during the actual launch. However, for some unknown reason, the CVP decreased immediately once the astronauts arrived in space. That is, the pressure outside the right atrium actually decreased (compared to the normal CVP measured on Earth) even though the body fluids continued to shift upward (Figure 22). Not only that, but CVP fell to a level below normal within one minute upon entering the space environment. This inflight response was totally unexpected and never predicted by Dr. Blomqvist's team. What could this mean? There must be some mechanism operative in the body that we don't fully understand related to how the body compensates for the "flood" of fluids accumulating around the heart while the astronaut is in space, and this unknown mechanism regulates CVP under these conditions. (Remember, sometimes a wrong prediction can actually teach you more than a "right" one! If you were always right, you wouldn't learn much!) These results have provided Dr. Blomqvist and other researchers with a new challenge - to understand why the force of fluids upward does not increase the pressure going into the heart once the astronauts reach the almost gravity-free environment of space. Figure 23 shows a graphic representation of the CVP data that was obtained for all three crew members.

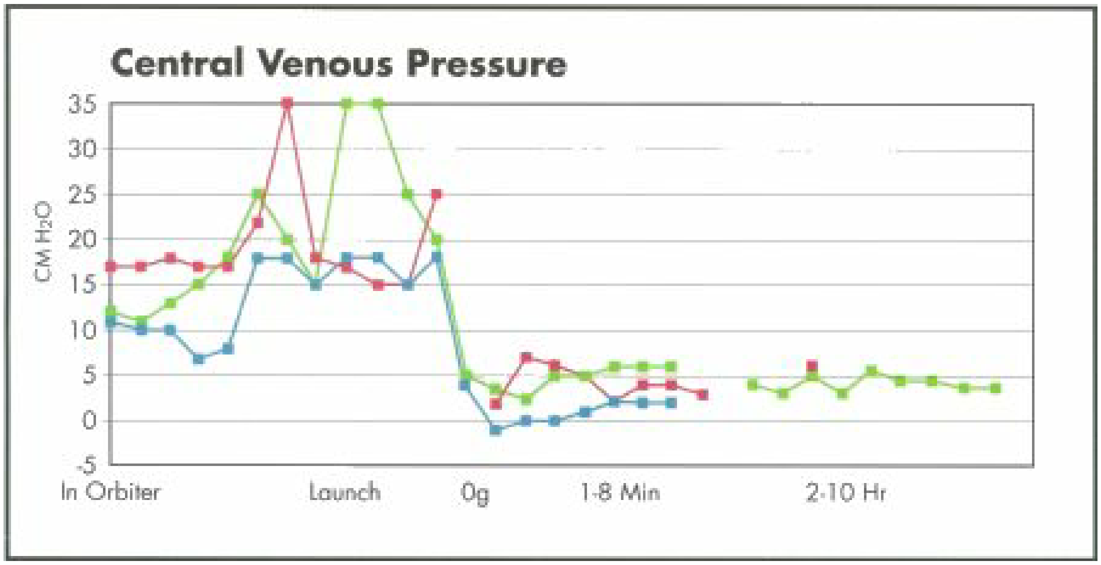


Figure 23. Central venous pressure measurements were obtained for three astronauts (indicated by different colors). Notice the dramatic COP changes that occurred during launch as well as when the astronauts arrived in space.

II. Heart Chamber Size and Volume

The heart is a muscle; in fact, it is the most active muscle in our bodies. All our other muscles are able to relax at one point or another, but **the heart muscle can never completely relax**. There are times when the heart muscle must work harder than other times, but as long as we are alive, it **never** gets a break from its constant responsibility of pushing the blood ever forward. The size of the heart is relatively small, about the size of an average adult fist, which seems unusual in light of the constant "exercise" it gets. The size of the heart and its chambers remains relatively constant throughout our lifetime, as long as we stay healthy and participate in a moderate amount of physical activity, and as long as we stay within the grip of gravity. It must be noted, however, that the heart chambers of marathoners can enlarge about 40% in response to an increased workload, and, along with enlargement of the chambers, the heart mass enlarges and the cardiac output increases 40% or more as well.

Here on Earth, gravity is both a help and a burden to the heart depending on what direction the blood must flow. Gravity assists the heart pump by pulling the flow of blood downward, but when the blood must flow upward, gravity must be overcome. So, what happens when an astronaut escapes the gravitational pull of Earth and travels into space? Gravity is no longer a participant that can affect the flow of blood throughout the body. Dr. Blomqvist and his team designed part of their experiment to quantify the effect of removing gravity on the size of the heart.

The left ventricle of the heart is surrounded by the most powerful part of the heart muscle. This is because the left ventricle is the chamber responsible for providing enough force to propel the blood out of the heart and into the long network of blood vessels around the body. The left ventricle is, in a sense, the most important chamber of the heart, and therefore is the most sensitive indicator of how our hearts are functioning. Any change in the size or volume of the left ventricle indicates a change in the work that the heart must perform for our bodies. Dr. Blomqvist's study was designed to measure the size of the left ventricle to obtain an indication of changes in the overall size of the heart, and therefore changes in the workload of the heart. But how does he measure the size of the left ventricle? Let's take a look.

Images of the size of the heart chambers give investigators information about the mechanical functioning of the heart. Echocardiography is a method that is used to obtain images of the heart, to watch how it functions, and to determine its size (Figure 24). This technique uses high-frequency sound waves (ultrasound waves that are above hearing range) that are transmitted into the body and that bounce off of the heart and are reflected back to a receiver outside of the body. The principle used here is similar to the principle behind an echo, which is a reflected sound wave. Let's look a little more closely at a type of echo that we are more familiar with in order to understand echocardiography a little better.

Figure 24. Echocardiography in space.

If a person, we'll call him Ron, stands on one side of a canyon and shouts "Hello!" toward the other side, an echo will be produced. The sound wave that is produced when Ron shouts travels through the air at the speed of sound (about 741 miles an hour) until it hits the opposite wall of the canyon, where it is reflected back toward Ron. Once the sound wave has been reflected it becomes an "echo." The echo travels back to Ron at the same speed of sound, and, after a brief period of time, Ron hears the echo. We have all probably participated in this type of echo experience.

If Ron has a stopwatch and a small electronic calculator, he can use this echo to calculate how far it is to the other side of the canyon. He simply measures the time it took for his shout to be echoed back to him. Suppose this was 4 seconds. He consults his handy conversion table, which tells him that 741 miles per hour is equivalent to 1087 feet per second. He then multiplies 1087 feet per second by 4 seconds and discovers that his "hello" traveled 4348 feet. Since this represented two trips across the canyon, one for the sound wave going and the other for the echo returning, he then divides by 2 and obtains 2174 feet as the distance to the other side of the canyon.

Ultrasound imaging (and echocardiography in particular) uses this same principle . Ultrasound waves are produced by a machine and directed into the body. The sound travels through the tissues at a constant speed until it encounters a reflecting surface, in our case, the heart. Once the sound waves bounce off the heart, some of the sound beam is reflected back toward the source; there it is received by the ultrasound scanner, which has been keeping track of the time and converting it to a distance in the same manner as Ron and his stopwatch. However, instead o f giving out the distance as a number, the scanner shows it as a dot on something like a TV screen. The position of the dot is proportional to the distance the echo traveled. This enables us not only to measure the distance but to get a visual picture of it as well. The pictures are taken, enabling a scientist to follow the changes in the heart over time, much like a movie.

This echocardiograph method was used by Dr. Blomqvist's team to obtain two-dimensional pictures of the heart. Images were obtained rapidly and in succession so that changes in the heart could be detected during all parts of the cardiac cycle. The images provided information on changes in heart size as the heart goes through its entire cycle. Dr. Blomqvist's team also developed a method to obtain a three dimensional model of the heart. This method can construct a model of the heart from a set of "sliced" images that were taken at different angles along the heart. These slices could be connected together to reconstruct the three-dimensional heart (Figure 25). This three-dimensional echo reconstruction technique was not used in space, but instead was used before and after the flight. The two-dimensional data that was gathered in space was videotaped for later detailed ground analysis; that is, data was not downlinked to the ground for immediate analysis.

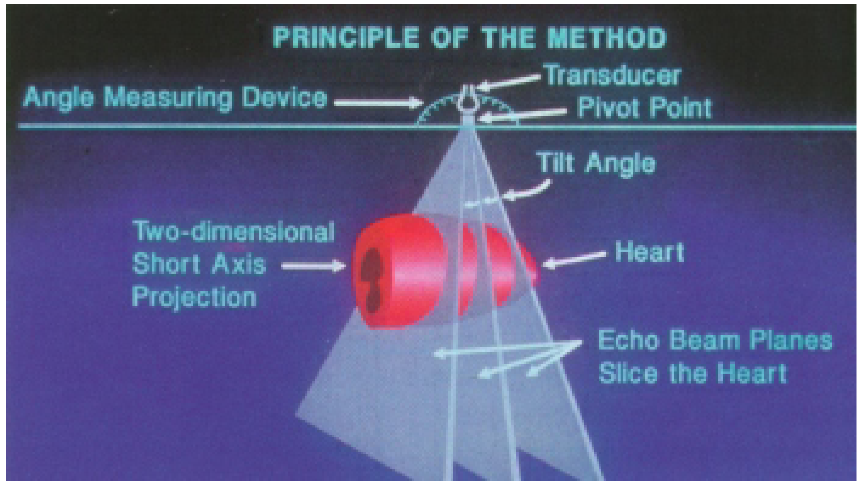


Figure 25. The principle behind the construction of the three-dimensional image of the heart.

As mentioned, echo images were obtained preflight, at various times inflight, and post flight. From these images, the investigators measured the length of the short-axis dimension of the left ventricle at a point in the cardiac cycle when the ventricle is at its largest size, the end of diastole. Remember, the diastolic period involves the filling of the heart. The end of the diastolic period is when the largest amount of blood is in the ventricle and it is immediately before the powerful systolic contraction. The volume of the **left ventricle** during this point, which is called the **left ventricular end-diastolic volume (LVEDV)**, was either determined through calculation (by cubing the length of the short axis, which was done for the inflight data) or determined by using the three-dimensional echo reconstruction technique described above (which was done preflight and postflight). Either technique will give very accurate volume measurements. Because the left ventricle is the largest chamber of the heart, any change in the volume of this chamber will reflect a change in the volume of the total heart.

The results indicate that the LVEDV, and therefore the total heart volume, increases dramatically when the astronaut first arrives in space (Figure 26). The LVEDV then begins to slowly decrease as the astronaut's body adapts to the space environment, ending up smaller overall compared with its size on Earth. These results were not surprising since similar measurements had been made on previous shuttle missions. The results, however, are difficult to explain.

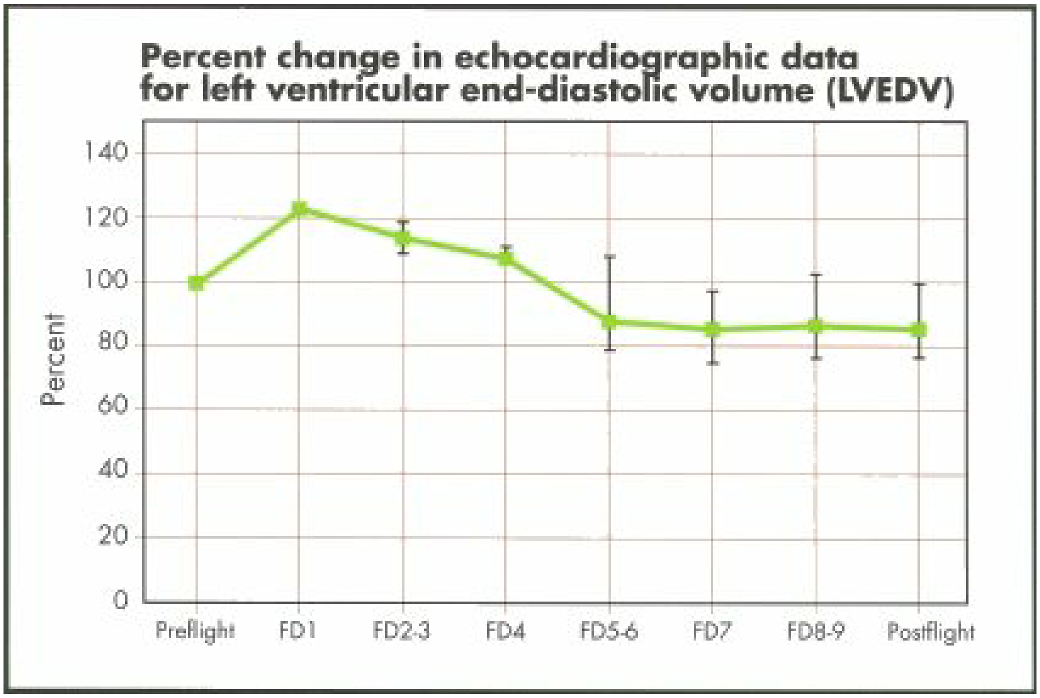


Figure 26. A graphic representation of the percent increase and subsequent decrease of the LVEDV in space compared to preflight levels on Earth. (FD = flight day)

Let's try to break the explanation into two parts. First, when the heart initially becomes larger in space, it is probably because of the increased volume of blood flowing into the heart. Remember, the body experiences an immediate shift of blood and fluids toward the upper part of the body. (In fact, this upward" shift of fluids begins while the astronaut is in the launch position waiting for the shuttle to take off.) Once in space, it takes the body about a day to eliminate this "flood" of fluids. This seems to correspond directly with the time in which we find the heart to be the largest: the first day. After the first day, the total amount of body fluids decreases below normal and continues at this level for the remainder of the mission.

This brings us to the second part of the explanation, which involves the heart shrinking in size after the first day in space. Once the excess blood and fluid have been eliminated, the heart no longer has to work so hard. This lower volume of fluids, along with the virtual absence of gravity, may be the factor responsible for the decrease in heart size that occurs after about the first day in space. Gravity, or the lack of it, is included in this part of the explanation because it no longer is a burden to the cardiovascular system. The heart has an easier time pumping the blood around the body when it does not have to pump the blood against the gravitational pull. A final point to make is that the weight-bearing muscles in the legs do not have to bear weight in space. That is, astronauts do not have to use the muscles in their legs the same way they do here on Earth. The less a muscle is used, the less oxygen is needed to fuel its activities. The less oxygen that is needed by the muscles, the less rapidly the blood must flow to deliver the oxygen to those muscles.

Dr. Blomqvist and his team of researchers will continue to investigate this very interesting change that occurs in space. The systems within the body are so interrelated that many other factors must be looked at in relation to this observed change in left ventricular volume. The physiological puzzle is just beginning to be put together. So many other pieces have yet to be found.

III. Static Leg Volume

One of the obvious physical changes that occurs in astronauts while they are in space is the phenomenon known as "bird legs." All astronauts experience this effect, in large part because of the shift of fluids away from the lower extremities to the upper part of the body. The legs become thinner, and as we've mentioned before, the face becomes puffier as fluids move upward. By measuring the **rate of change** of the circumference of the legs, scientists can obtain some idea of the extent and speed of the fluid shift that occurs in space, particularly during the early part of the mission when most of the shift is taking place. After the mission, this also becomes an important indicator of how fast the fluid returns to the lower part of the body.

An important way to monitor the head ward shift of fluids in the body, then, is to measure the changes that take place in the size or volume of the legs. Static leg volume (static = still, not moving) measurements in space are one of the easiest measurements to carry out. There is no need for special electronic equipment or complicated procedures. The measurements, however, must be made very carefully so that we can obtain the most accurate measurements possible. Changes in leg circumference (the distance around the leg, also known as girth) are measured by using a technique known as **plethysmography** plethora = fullness). This is a very fancy word for a very simple technique that measures the "fullness" of the leg.

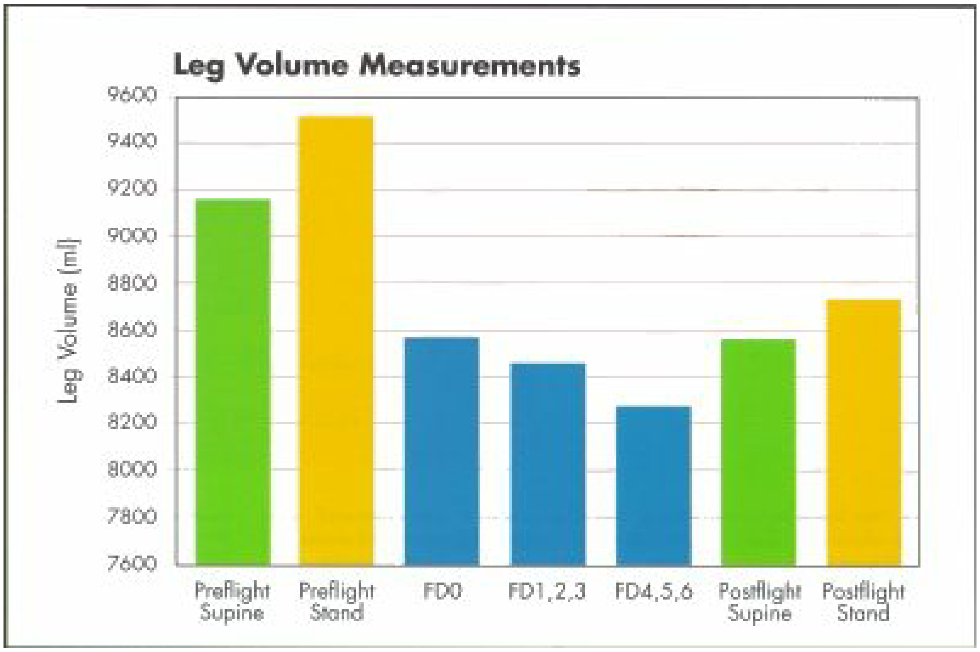
The technique uses an expandable leg "stocking" that the astronaut wears over the full length of the leg (Figure 27). Attached to the stocking are nonexpendable longitudinal measuring tapes placed at eight different heights along the leg. Before the mission, at various times during the mission, and after the mission, measurements are made by wrapping the measuring tapes around the circumference of the leg and recording the length of the tape. In space, as the leg becomes thinner, the tape measurement decreases. When the astronauts return to Earth, the leg circumference increases, and therefore the tape measurement increases.

Figure 27. A plethysmography device measures leg circumference change.

How then is the volume of the leg determined from the tape measurements? The volume is calculated using the assumption that **each leg segment** (between each tape) approximates a truncated (cut off at the top) cone. The basis for this assumption is illustrated in Figure 28. The volume of each segment of the leg is calculated using the equations shown in Figure 28. As we know, the leg segments that are identified are not shaped exactly like a truncated cone, but, in many cases, they are similar enough to feel confident that we are coming close to the actual volumes that we are interested in. If the leg that we are measuring is shaped very irregularly, this technique would not work very well. In that case, the segments would be made smaller so that each segment would contain less of the natural curve of the leg. Also, the thickness of the tape-measure fabric must be corrected for in the final calculation to make sure that the circumference measurement would not be affected by the tape thickness.

As you can see, the measurement of the volume of the leg is a relatively easy one to make. But it is the **rate of change** of the leg fluid volume that we are interested in. That is, how fast does the fluid leave the leg area? Therefore, in space, the leg volume measurements must be taken early and over a period of time to understand how fast the fluid leaves the lower part of the body. Although leg volume measurements have been made on astronauts in space for many years, Dr. Blomqvist's team was able to take the earliest measurements of such change. In fact, the inflight measurements were made on the first day in space. This is important because we know the fluid begins to shift "upward" while the astronaut is waiting in the shuttle to launch, and we also know that there is a dramatic fluid shift immediately after the astronaut arrives in space (Figure 29). For missions up to two weeks, the leg volume continues to decrease until the astronaut returns to Earth.

Figure 29. Leg volume measurements preflight, insight, and postflight. (FD = flight day)



Now, let's attach the results from Figure 29 to the fluid shift phenomenon, which we know takes place during the early part of the mission. If the body eliminates the excess fluid by the end of the first day, then why does the leg volume continue to decrease? This is a very good question. Dr. Blomqvist hypothesizes that the leg-volume decrease that occurs after the first day or two is not a reflection of the fluid shift but instead is a reflection of the fact that the muscles are not being used in space. That is, the astronauts begin to lose muscle strength because they are not using their muscles to stand up. As muscles become weaker, they lose their mass. Therefore, the decrease in leg volume after the first day in space is probably due to the decrease in muscle strength and mass. This hypothesis is further supported by the postflight data shown in Figure 29. During the postflight measurement, the leg volume is shown to increase, but not to the preflight level. This is probably because the astronaut's muscles have become smaller due to their lack of use in space.

IV. Cardiovascular Function During a Stand Test

One of the most important points to make throughout this book is that the human condition on Earth and the human condition in space are not only different, but they are appropriate for their respective environments. Another way to put this is that our bodies function in an "Earth-normal" condition while on Earth and a "space-normal" condition while in space. Everything that we have learned so far indicates that when an astronaut is in space, all the changes that occur in the body are absolutely appropriate for the space environment. **Any problems that occur do so only when the astronaut returns to Earth.** The body has undergone so many changes while in space that it no longer tolerates the gravitational pull on Earth very well. In particular, the astronauts are known to have great difficulty standing upright and are said to be suffering from **orthostatic intolerance** (orthostatic = standing upright, intolerance = unable to handle).

Standing upright represents a particular challenge to returning astronauts because it is in this position that gravity is exerting most of its influence on the cardiovascular system. Think of an upright human body as a tall column of water (after all, our bodies are composed primarily of fluids anyway). As gravity is pulling down on that column of water, each level, or depth, of water is influenced. In any body of water, the pressure at the surface of the water is equal to atmospheric pressure, but the pressure rises 1 mm Hg for each 13.6-mm distance below the surface. This pressure results from the weight of the water above it and therefore is called **hydrostatic pressure**.

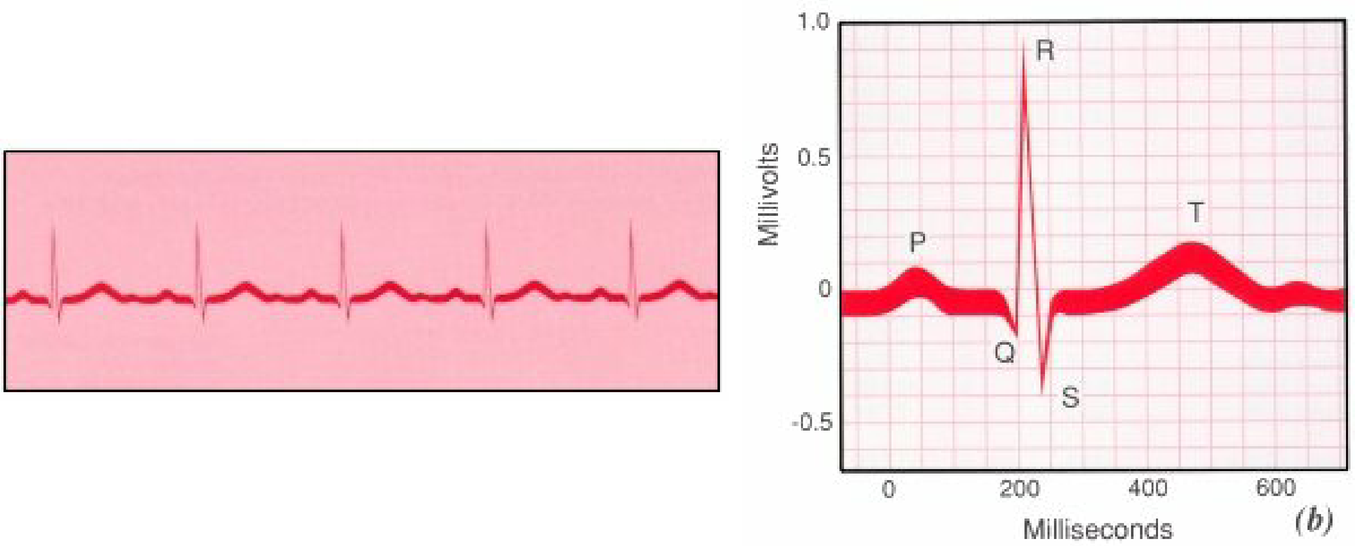
Hydrostatic pressure also occurs in the vascular system of the human being because of the weight of the blood in the vessels. Hydrostatic pressure exists on Earth because of gravity. When an astronaut has spent time in space, the astronaut's cardiovascular system has adjusted to functioning without gravity. The astronaut loses about 20% of the fluid in his or her body and is feeling fine. Also, the various mechanisms that control our cardiovascular function here on Earth have been greatly relieved of their duties while in space and away from the Earth's gravitational pull. Gravity deals a mighty blow to the system when the astronauts return. Many astronauts cannot tolerate standing for any length of time upon their immediate return to Earth, and, in fact, some astronauts have actually fainted when asked to stand up for even short periods. We know that gravity has a great deal to do with that, but what in the cardiovascular system is specifically causing this phenomenon?

Dr. Blomqvist's team put together a series of cardiovascular function tests to measure the extent of orthostatic intolerance as soon as possible after the astronauts return to earth. The full series of tests was conducted both preflight and postflight. The preflight measurements served as baseline control measurements from which to compare the postflight data. These measurements gave us an indication of what may be happening in the body to produce this "weakness" in astronauts when they stand against the clutches of gravity after being in space. Thus, the entire test is referred to as a stand test. If the mechanisms that produce orthostatic intolerance can be determined, we can then concentrate on developing specific countermeasures (steps that we can tak e to fight back, or counter, these effects). The specific measurements that were made included mean arterial blood pressure (MBP), heart rate (HR), and cardiac output (CO). From the heart rate and cardiac output values, stroke volume (SV) was calculated. Table 6 is a list of the raw data (individual data for each astronaut that has not been analyzed) that Dr. Blomqvist obtained during both the preflight and postflight stand test. It is left to you and your teacher to decide how to best analyze this data.

The stand-test protocol consisted of a 29-minute supine (Lying face up) period during which the astronauts were instrumented with the various electrodes on the chest to measure HR; a blood pressure cuff on the arm and one on the finger to measure blood pressure two different ways; and a stocking plethysmograph to measure leg volumes. after instrumentation was complete, a set of supine measurements was obtained. Next, the astronauts were asked to stand up for a 10-minute period, and during this time measurements were taken again. This protocol was performed on each crew member preflight and then within the first four hours after their return to Earth.

An electrocardiograph was used to actually determine the astronaut's HR. An electrocardiograph measures the electrical activity of the heart and displays it as a set of pulses on an electrocardiogram, that correspond to different parts of the cardiac cycle. HR information can be accurately obtained by measuring the length of a complete cardiac cycle (Figure 30). HR was monitored and recorded continuously in this way.

Figure 30. (a) An electrocardiogram (ECG) displays pulses that correspond to the different parts of the cardiac cycle. A normal ECG is shown. (b) In an ECG pattern, the P wave results from the contraction or squeezing (depolarization) of the atria, the QRS complex results from the squeezing (depolarization) of the ventricles, and the T wave results from the filling (repolarization) of the ventricles. Heart rate information can also be determined using the time axis corresponding to the ECG pattern.



Indirect arterial blood pressure was measured by two different methods. One method used a typical arm cuff of the kind that is used in your doctor's office. The other method recorded continuous finger blood pressure. Both methods were used to double check the accuracy of the measurement. Also, leg volume was determined using the stocking plethysmograph. Leg volume was measured during the supine resting period and after 6 and 10 minutes of standing. The leg volume data was presented in an earlier section.

Cardiac output was estimated by a special **rebreathing technique**, which measures pulmonary blood flow. Remember that the lungs work so closely with the heart and blood vessels that certain heart function measurements, such as cardiac output, can actually be obtained from measurements of pulmonary function. That is, measurements that involve breathing can actually yield information about blood flow through the heart. This works because all the blood that flows into the lung's capillaries to be oxygenated equals the amount of blood that flows out of the heart. Blood flow through the lungs is called **pulmonary blood flow (PBF)**. Thus

cardiac output = PBF

The rebreathing technique uses a system called the **cardiopulmonary rebreathing unit (CRU)** that is attached to a **gas analyzer moss spectrometer (GAMS)** that can analyze the chemical content of a gas mixture {Figure 31). During the rebreathing maneuver used to measure PBF, the astronaut breathes in and out of a rebreathing bag, hooked to the CRU, that is filled with a known mixture of very safe test gas that is different than normal atmospheric air. This gas is not only safe, but the different chemicals in the gas can also be easily analyzed by the GAMS. When the astronaut breathes in the test gas and then expires back into the rebreathing bag, the mass spectrometer determines how much of the test gas has been absorbed by the astronaut's lungs. The astronaut repeats this rebreathing maneuver for a specified period of time, breathing in and out of the rebreathing bag. After each breath, the spectrometer determines how much more of the test gas has been absorbed into the astronaut's lungs. The amount of gas that is absorbed by the lungs is proportional to the amount of blood that passes through the lungs. As already mentioned, the amount of blood that passes through the lungs (PBF) is equal to the amount of blood that flows out of the heart (cardiac output). Therefore, this is an indirect way to measure cardiac output (CO).

Figure 31. The cardipulmonary rebreathing unit (CRU) and the gas analyzer mass spectrometer (GAMS) being used in space to determine cardiac output.

Finally, stroke volume (SV) was calculated after determining both CO and heart rate (HR) by using our well-known relationship:

CO = SV x HR or SV = CO/HR

At least three measurements were made while the astronauts were in the supine resting position, followed by measurements after 5 and 10 minutes of standing.

The MBP, HR, CO, and SV values that were obtained during the postflight stand test will not tell scientists anything about what is causing the orthostatic intolerance. Instead, these values are only indicators of what is happening within the body and can only suggest what might be causing the problem. They will help scientists determine which cardiovascular control mechanisms to begin looking at in detail. That is, they will help scientists sharpen their hypothes about the actual mechanisms of action behi nd orthostatic intolerance and about what should be done to help the astronauts better tolerate their return to Earth. It must be emphasized here that the astronaut's cardiovascular system **does return to normal**, in most cases within a few days.

V. Cardiovascular Function During Exercise

A common technique used as a measure of cardiovascular strength involves looking at how the heart and lungs are able to work together under conditions of extreme exercise. You may know someone who suffers from heart disease and who has undergone testing to measure the extent of his or her health problem. Most likely that person was first put through an **exercise stress test** so the physicians could evaluate the ability of the heart to pump blood fast enough to meet the body's increased oxygen need. The pain that a patient may experience during such a test will indicate to the doctor that blood, and therefore oxygen, is not being delivered in the appropriate amount to certain parts of the body.

An exercise stress test can also be used for research purposes using healthy individuals to determine the limits of aerobic capacity. The anal common denominator in athletic events is what the muscles can do. But a primary measure of muscle performance is **endurance**. To a great extent, endurance depends on nutritional support for a muscle. The most important determinant of nutritional support to a muscle is how well the heart and lungs can supply the muscle with oxygen when the muscle energy demands are at their maximum level.

What happens to the ability of the cardiopulmonary system to supply the body with needed oxygen under physically stressful conditions in space? This question has tremendous implications for future missions, particularly as we are faced with the need to build a space structure for humans to live in while working on the next generation of space life sciences studies. We must determine if humans are able to work physically hard in space to build those structures and to work in them for a period of months. In addition, we would like to know how much an astronaut's work and exercise capacity is affected by orthostatic intolerance after the astronaut returns home.

The ability of the body to consume oxygen is a determinant of how much exertion a person can withstand. That is, the **oxygen uptake** capability of the body will determine how much endurance a body has and therefore how hard a body can work. (When the body is exercising at its maximum capacity, the oxygen uptake is known as **VO_2 max** where V = velocity or rate and O_2 is, of course, the symbol for molecular oxygen.) The oxygen uptake depends on two things: how well the respiratory system can ventilate (bring air into) the lungs so that there is enough oxygen to feed the blood, and how fast the heart can pump oxygenated blood to the muscles. How fast the heart can pump blood to the muscles also depends on two things: the heart rate and the stroke volume. Remember, **heart rate x stroke volume = cardiac output**. Therefore, a measurement of oxygen uptake (VO_2 max), cardiac output, and heart rate will give researchers the data to determine the heart's pumping ability and the respiratory system's ability to bring air into the lungs during exercise.

Dr. Blomqvist's team examined the exercise capacity of the astronauts before the flight, while in flight, and after the flight by putting the astronauts through a maximal exercise routine, or by assigning them the most exercise they can handle. He was interested in knowing if the changes that occur to the cardiovascular system in space affect the ability of the astronauts to exert themselves. The question he asked was whether or not the almost complete absence of gravity caused any impairment of the cardiac pump function and/or of major cardiovascular regulatory mechanisms under conditions of stress (exercise). In particular, his experiment examined cardiac output (CO), heart rate (HR), stroke volume (SV), and oxygen uptake at maximal exercise levels (VO_2 max).

Each person's maximal exercise level is unique to just that person (Figure 32). Fitness level, age, sex, medical history, and chemical and hormonal variations are all factors that influence how much **power** (the amount of work performed over a certain period of time) a person can produce when exercising to the maximal limit. Therefore, to understand each astronaut's maximal exercise capacity, the level of power produced by each astronaut was measured at the same time that the cardiovascular measurements (VO_2 max. CO, HR, and SV) were taken. The astronaut's power output was determined preflight as a control (or baseline) value to serve as a point of comparison for the inflight and postflight values.

Figure 32. A marathon runner has one of the highest levels ofendurance of any human being. Their hearts are up to 40% larger and arecapable of pumping 40% more blood than other very athletic individuals.

Power output is determined by measuring how much work the astronauts performed while exercising at their maximum level and then dividing that work by the time it took to do it. In physics terms,

$$\text{work} = \text{force} \times \text{distance}$$

and

$$\text{power} = \frac{\text{work}}{\text{time}} = \frac{\text{force} \times \text{distance}}{\text{time}} = \text{force} \times \text{veloci}$$

Note that distance/time = velocity. For instance, velocity can be expressed in miles/hour.

Typical units that are used to describe work are: kilocalories, ergs, joules, BTUs (British thermal units), and foot-pounds.

Typical units that are used to describe power are: kilocalories/minute, ergs/second, joules/second (also known as **watts**), BTUs/hour, and foot--pounds/second. (Just as a note of interest, another unit that is probably the most commonly recognized power term by the general public is horsepower. Actually, horsepower was suggested as a unit to represent the power actually delivered by a horse, but one horsepower is really equal to 550 foot-pounds/second as well as 746 watts.)

Notice that the power units are basically the same as work units, except that they are divided by a time unit. Thus, again, power = work/time.

How is power determined for each of the astronaut's exercise sessions? When exercising, the astronauts use a bicycle ergometer, which is simply a computerized exercise bike. The computer on this bicycle ergometer can determine the amount of power generated by the astronaut based on the force that the astronaut applies to the pedals (force) and how fast the astronaut is pedaling (velocity). The power (force x velocity) is recorded in units of watts.

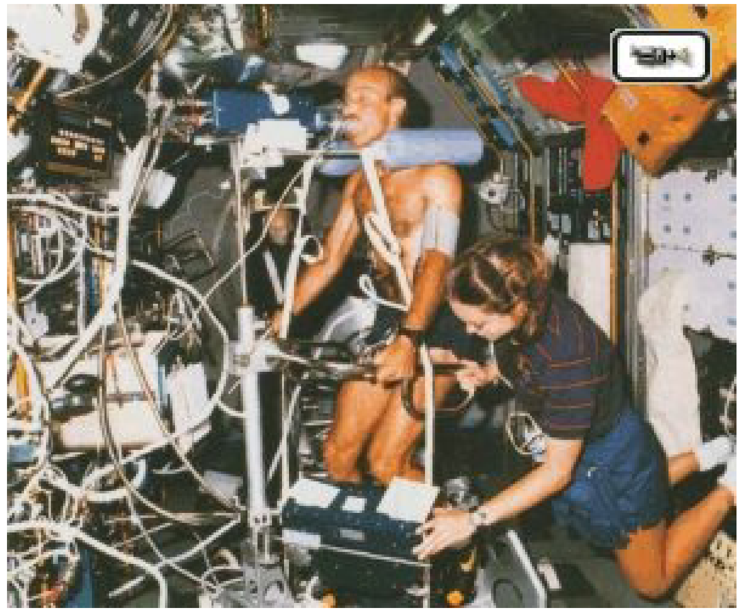


Figure 33. An astronaut can achieve maximal exercise levels using a bicycle ergometer in space.

As mentioned previously, the maximal exercise test was carried out by the astronauts before flight in order to establish their control or baseline measurements for comparison with inflight and postflight performance. The astronauts reached their maximal exercise level by using a bicycle ergometer that has been specially designed for use in space (Figure 33). Can you imagine trying to stay seated on an exercise bike without gravity? The space version of this piece of hardware has been equipped with special shoulder pads that are attached to the bike and that hold the astronaut down during exercise. Electrodes were attached to the astronaut to obtain heart rate information through use of an electrocardiograph. The astronaut also used the rebreathing technique (using the CRU and the mass spectrometer) described in the last section for the determination of cardiac output. Stroke volume was calculated using our famous equation, CO = SV x HR.

Oxygen uptake (VO2 max) was measured using a technique that is similar to the rebreathing technique used to determine cardiac output (we covered this in the last section). While exercising, the astronauts breathed in and out of a tube that was hooked to a gas analyzer mass spectrometer (GAMS). The GAMS was used to determine the fraction, or concentration, of various chemicals in the air. This GAMS was able to measure the concentration of oxygen in the air (the amount of oxygen molecules in a fixed volume of air) that the astronaut breathed in and compare that with the concentration of oxygen that was breathed out. The idea is simple: the concentration of oxygen breathed in minus the concentration of oxygen breathed out equals the amount of oxygen that was consumed by the astronaut, or in - out = consumption

Thus, the spectrometer measured how many liters of oxygen were consumed by the astronaut out of the total liters of air that the astronaut breathed in, to yield the number of liters of oxygen/liters of air.

At the same time that the oxygen was measured, the rate of ventilation was determined using a turbine flowmeter that was inside the tube. As the astronaut breathed in and out, the flowmeter measured how many liters of gas were breathed per minute. Thus, it measured the flow rate of air into and out of the astronaut's in units of liters of air/minute.

Let's do a some dimensional analysis to figure out the units for oxygen uptake:

$$\text{Oxygen uptake} = \underset{\text{consumed}}{\text{concentration of oxygen}} \times \underset{\text{breathed}}{\text{flow rate of air}}$$

$$\text{Units}: \quad = \frac{\text{liters of oxygen consumed}}{\cancel{\text{liters of air}}} \times \frac{\cancel{\text{liters of air}}}{\text{minute}}$$

$$= \frac{\text{liters of oxygen consumed}}{\text{minutes}}$$

Let's take a look at the results. The inflight results were somewhat surprising since they do not differ significantly from the preflight values (Table 7). This suggests that the maximal systemic (referring to the blood flow around the body) oxygen transport mechanisms are well maintained in space. This means that the heart's pumping capability is preserved in space even though the cardiovascular system is changing and adapting to the space environment. It also means that the pulmonary contribution to oxygen delivery around the body is still in good shape.

Now, look at the postflight data. This is where the effects of space flight become clear. **It is when the astronauts return from space that the cardiovascalar deconditioning becomes evident**. As you can see, there was a significant decrement in performance **postflight** compared to **preflight** values. First of all, the astronauts were generally not able to reach the maximum power output during exercise postflight compared to preflight. Also, oxygen uptake during maximal exercise (VO_2 max) was significantly lower than preflight values. Why? Look at the cardiac output and stroke volume values. The heart is simply pumping much less fluid out with every heartbeat. This is certainly caused in part by the lower volume of blood and fluids that are flowing in the astronauts' bodies and, probably, by the smaller size of the heart.

The interesting point about the cardiac output reduction is that of the two variables that determine cardiac output (HR and SV), heart rate is not significantly different, but stroke volume is. The fact that heart rate remains about the same indicates that, although the body is trying to operate with much less fluid, at least the heart-pumping action has not been significantly affected by space flight. Therefore, the heart **can still pump as fast** under extreme conditions of stress as it did before the astronaut went into space. However, the fact that the stroke volume changes significantly suggests that the heart **cannot pump as much** blood with each beat during the postflight exercise stress compared to preflight.

Table 7. Preflight, insight, and posflight maximal exercise data (CO = cardiac output, HR = heart rate).

MAXIMAL EXERCISE TEST DATA

	Power Output (Watts)	VO_2max (liters/min)	CO (liters/min)	HR (beats/min)
PREFLIGHT	233 ± 63	2.76 ± 0.81	18.9 ± 2.3	179 ± 17
INFLIGHT	211 ± 59	2.65 ± 0.64	N/A	170 ± 24
POSTFLIGHT	200 ± 78*	2.14 ± 0.49*	14.5 ± 2.5*	176 ± 15

*- measurement is significantly different from preflight.
N/A- data not available

Overall, it can be said that even though the heart pump seems to be operating fine, the body's ability to transport and use oxygen changed while the astronaut was in space. Not only was the stroke volume greatly reduced, but the oxygen uptake capability of the body (VO2 max) was also reduced. One reason seems to be that the body has less fluids to circulate around the body. Without an adequate oxygen delivery system, the body cannot exert itself as it did before traveling into space. The good news is that the astronauts regain their endurance after a few days or maybe weeks of being back on Earth.

CONGRATULATIONS!

We have just completed our examination of Dr. Blomqvist's space flight results. You have been presented with a great deal of information that is rather complicated, but now is the time to take what you have learned, break it into smaller pieces, and communicate it to others. Remember, **all of this information and knowledge is worthless unless we are able to communicate and share it with the rest of the world**, even if that world includes only those in your classroom. It is a big part of a scientist's job to prepare prese ntations for people so they can share their results. In fact, it is a very big part of an astronaut's job to deliver presentations so others can share some of the excitement of their scientific and personal experiences in space. So let's move on to learn how to prepare an effective and informative scientific presentation so that you can share Dr. Blomqvist's space flight results with those around you.

SPEAKING OF SPACE

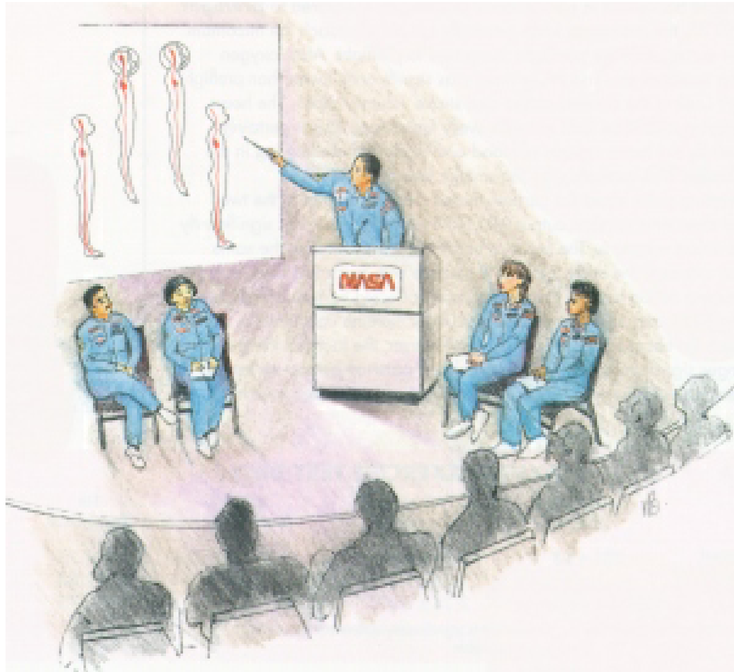


Figure 34: One of the most important jobs that astronauts have is to deliver presentations and share their experiences with other people.

One of the most important parts of being a scientist is being able to present the results of an experiment clearly to other scientists, to students, and to all of us, so that we can learn from it and help science move forward to new and better ideas and questions. We are now going to participate in an activity to help us better understand how to present scientific results to those around us. The scientific results that you have just examined are broken into five sections. For this activity, you will break into five small teams with the help of your teacher. Each small team will take one of the five sections and develop a plan for presenting the information in a clear and concise way. In the development of your presentation, you should take into consideration the following points:

1. Imagine that your small group is the actual scientific team that conceived planned, and carried out the experiment. Of course, it was the astronauts who actually carried out the inflight portion of the experiment, but your role was to oversee all the activities and make sure that they were trained appropriately to do the right job.
2. Design your presentation cars if your audience has never heard the information before. This means that you must first provide enough background for your audience to understand the significance of the study. That is, explain why this study is important. Keep the audience foremost in your mind as you design your presentation and always make it as easy as possible for your audience to understand.
3. Present information about the hypothesis, your methods, and the results. Remember that a hypothesis should be a simple, basic statement about what you expect the results to indicate. Develop your own hypothesis based on what was actually expected before the results were obtained. The description of your methods should include information about your protocol, the equipment that was used and how it was used, information about who the subjects were and how many there were, and anything else that is relevant about your study. In planning for your presentation, you must also determine the best way to display your results. You may want to graph the data or present a table of values. If you choose to produce a graph, include a title, the units of measurement on each axis, and a legend, and you should make it as clear as possible. Also, remember to tie the results of your study back to the hypothesis.
4. Explain what the results indicate about how the body responds to space flight. Also try to determine how the results might affect our understanding of human physiology here on Earth. Indicate which, if any, health problems that we encounter here on Earth might be helped by the knowledge you have gained from your space flight results.

Keep in mind that there are literally dozens, and sometimes hundreds, of people involved in carrying out a space flight investigation, each of whom is responsible for his or her very own specific aspect of the study, and each of whom is absolutely necessa ry to the success of both the individual experiment and the overall mission. There should be plenty of different roles for the different members of your team. There should certainly be a principal investigator who is in charge of the whole study, just as Dr. Blomqvist was in charge of the real study that we've been learning about in this chapter. Also, a member of your team might serve as the engineer involved with the equipment. Another member of your team might be a physician or a physiologist assigned to make sure all of the experimental procedures are carried out safely. This is particularly important because the safety of the astronaut is always the first consideration. There might also be various technicians responsible for collecting the data or producing the graphics. There are plenty of jobs for everyone. You may want to use more than one person to present the experiment to your audience. Don't be afraid to use plenty of visual aids. Be imaginative, but also be faithful to the main objectives of your experiment.

After each presentation, there should be a short question and answer (Q&A) period so that the audience has the chance to ask relevant, thoughtful questions. Rely on your team members to help you answer the questions. Don't let this Q&A session scare you. It is always a part of any well-planned presentation. Remember, you will be on the other side of the fence asking questions of all the other groups!

Good luck!

REVIEW QUESTIONS

Earth Physiology

1. Describe an analogy that you feel represents the system of blood vessels and how it functions.

2. Describe the gas exchange process which takes place in the lungs, including what blood cells are involved.

3. Name four factors that affect arterial blood pressure and explain their effect on arterial pressure.

4. Describe the three stages of respiration.

5. Explain how inspiration occurs and the effect of atmospheric pressure on it.

6. Why is pulmonary blood flow equal to cardiac output?

7. As blood flows through the heart, what structures prevent the backward flow of blood? Make a sketch of the heart and identify the structures.

8. Describe the capillaries and identify their major functions.

9. Give the definition of the following respiratory measurements.
    a. Tidal Volume
    b. Inspiratory Reserve Volume
    c. Expiratory Reserve Volume
    d. Residual Volume

Space Physiology

1. What is the affect of gravity on the flow of blood?

2. State the parts of an experiment that a scientist must design and carry out to support or refute the assumptions made about the study of interest.

3. A. If you designed an experiment and the data did not support the hypothesis how would you use this information?
   B. Can you learn more from being right or being wrong?

4. What is the physiological occurrence that causes the "puffy-head syndrome" in an astronaut in space and what is the physical factor that is involved?

5. What happens to the central venous pressure (CVP) reading when an astronaut is on the launch pad, during his/her exposure to the high g-levels during the launch and in space?

6. Explain what happens to the heart while in space and why.

7. Human function on Earth and in space differ. Describe how scientists explain the differences.

8. What abnormal condition is observed in astronauts after they return to Earth? What is it called and how do doctors test for it in the returning astronaut?

CRITICAL THINKING

1. In a mixture of gases, the individual gases are responsible for a proportion of the total pressure produced by the mixture. The pressure that each gas creates is called partial pressure. Air is 21% OF and, therefore, is responsible for 21% of the total atmospheric pressure. Diffusion of oxygen from the alveolus into the blood cells of the capillaries is a result of differences in partial pressure. Since the partial pressure of O2 is greater in the alveolus, it moves into the blood. On the other hand the partial pressure of CO2 is greater in the blood, causing it to diffuse from the blood into the alveolus.

   Given: Atmospheric pressure of 760mm Hg
   Find: Partial Pressure of Oxygen

2. Describe the pathway of a red blood cell {RBC) as it travels through the heart.

3. A. If an astronaut stands "upside down" on his/her head in space, does blood rush to his/her head like on Earth? Explain.
   B. What normal, everyday activities would be difficult, if not impossible, to carry out in the microgravity environment of space?

References

Certain parts of the text were excerpted and adapted from the following publications and other references:

For the section describing Earth Physiology:

1. Fox SI (1987). ***Human Physiology*** , 2nd ed. William C Brown Publishers, Dubuque, lowa.
2. Guyton AC (1986). ***Textbook of Medical Physiology*** , 7th ed. WB Saunders Company, Philadelphia, PA.
3. Oram RF (1989). ***Biology: Living Systems*** . Merrill Publishing Company, Columbus, OH.

For the section describing the space flight results and as influence for numerous figures and tables:

1. Blomqvist, CG (1994). ***SLS-1 Final Report: Cardiovascular Adaptation to Zero Gravity.*** University of Texas Southwestern Medical Center, Dallas, TX.
2. Buckey JC, Garney FA, Lane LD, Levine BD, Watenpaugh DE, Blomqvist CG (1993). Central venous pressure in space. ***New England Journal of Medicine*** , 328:1853-1854, 1993.
3. Thoynton WE, Hedge V, Coleman E, Uri JJ, More TP (1992). Changes in leg volume during microgravity simulation. ***Aviation, Space, and Environmental***

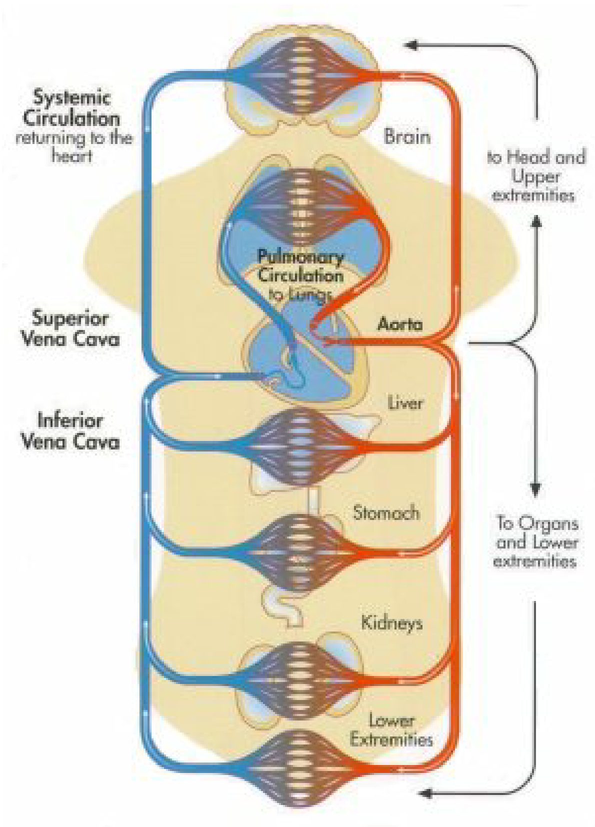


Figure 7. Representation of the circulation,showing both the pulmonary circuit that feeds blood through the lungs and the systemic circuit that feeds blood to the rest of the body.

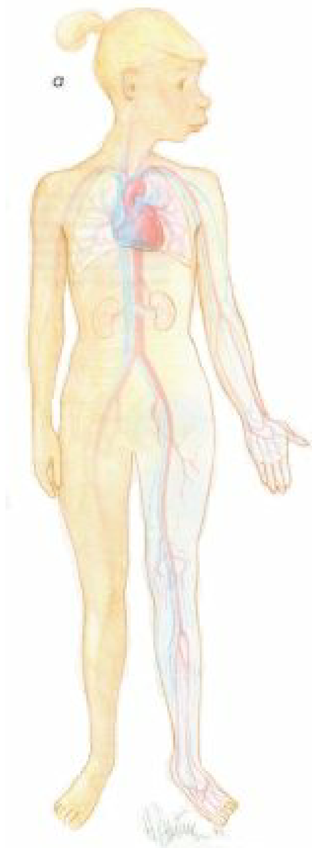


Figure 8a. The cardiovascular system. The arterial blood (red) contains oxygenated red blood cells (RBCs), and the venous blood (blue) contains deoxygenated blood.

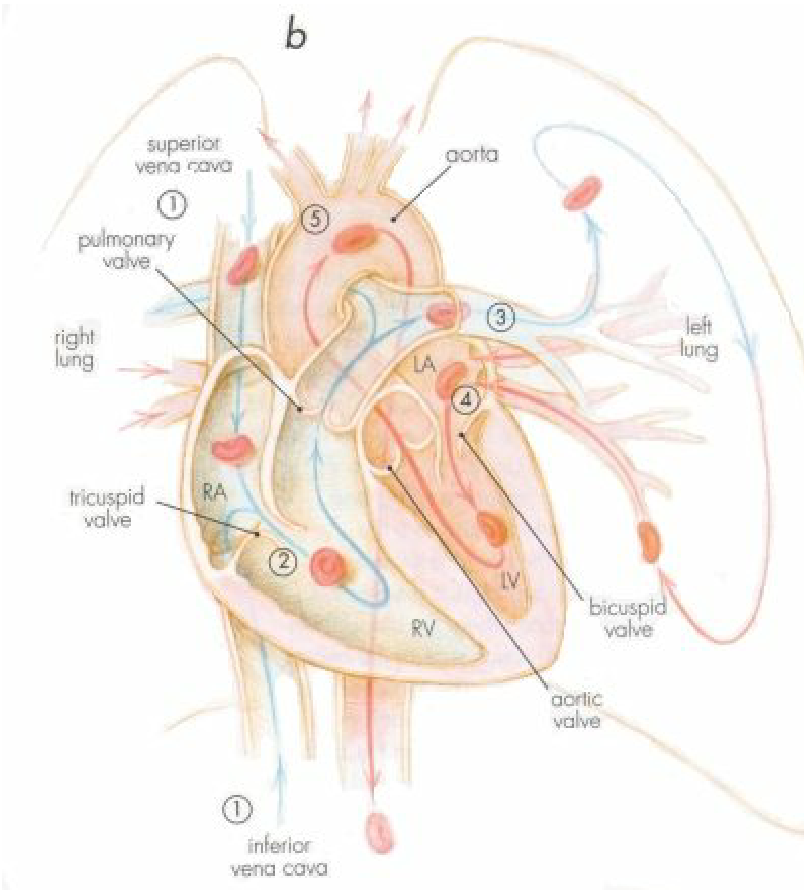
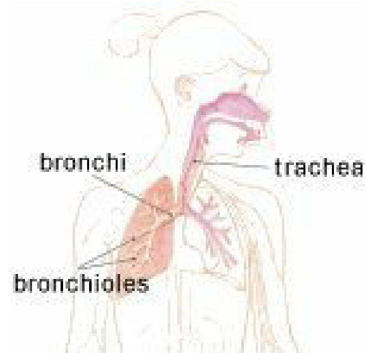


Figure 8b. The path of a typical RBC through the heart: The deoxygenated RBC (1) enters the right atrium (RA) through the superior or inferior vena cava; (2) travels through the tricuspid valve into the right ventricle (RV); (3) continues through the pulmonary valve into the pulmonary artery and into the lungs; (4) returns, oxygenated, through the pulmonary vein into the left atrium (LA) and continues through the mitral valve and into the left ventricle (LV); and (5) flows through the aortic valve into the aorta and back out into the body.

Figure 12. (a) The respiratory tract through which air enters the cardiopulmonary system.



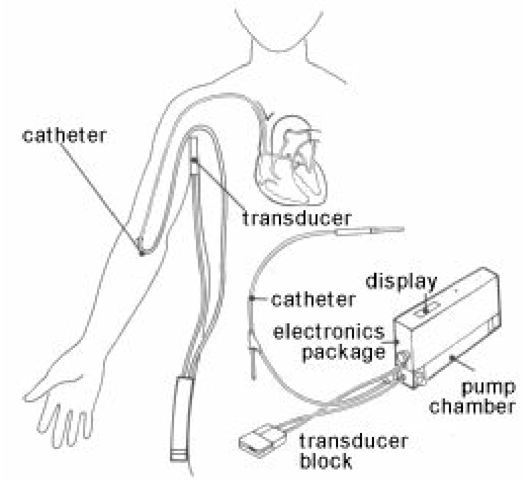


Figure 18. To measure central venous pressure (CVP), a catheter is placed in an arm vein and advanced through the vein to just outside of the right atrium, where all the blood from the body enters the heart. A transducer is placed in the armpit at the same height as where the catheter tip is placed outside the right atrium. Pressure travels from the catheter tip to the transducer. Ther transducer transforms the pressure into a voltage signal that the CVP recording unit can recognize.

Figure 21. During a shuttle launch, the forces on the body are equivalent to about three times the normal force of gravity that the body experiences on Earth.

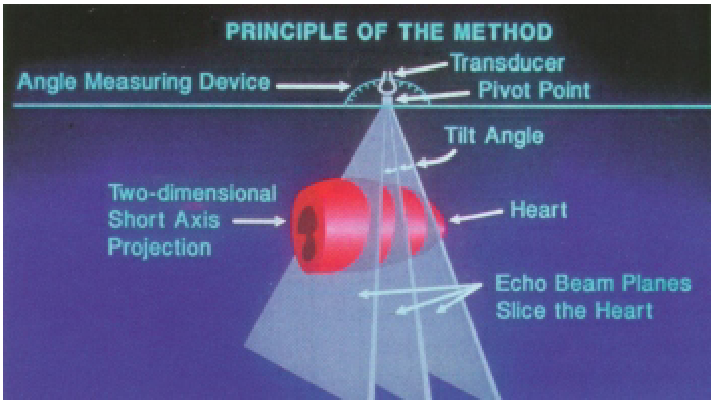


Figure 25. The principle behind the construction of the three-dimensional image of the heart involves combining (through use of a computer) the two-dimensional images of different slices of the heart that were obtained at different angles.

Figure 27. Changes in the circumference of the leg are measured using a plethysmography device that fits around the leg with Velcro straps. As the leg shrinks in circumference, the length of the Velcro straps around the leg changes and the measurements are recorded.

Figure 28. Segment locations and the equations for the calculation of leg volumes (c = circumference, h = height, r = radius). The fabric thickness of the stocking was subtracted to obtain an accurate measure of the leg circumference.

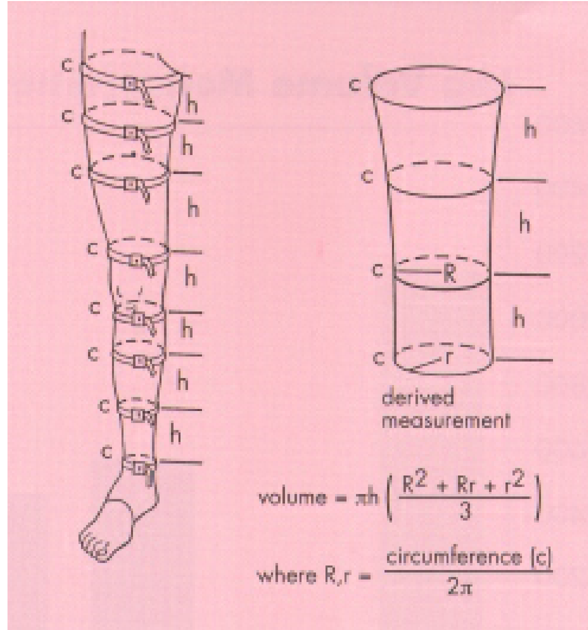


Table I. Definitions of respiratory measurements.

Tidal volume	The amount of air that moves in or out in one normal breath (~500 ml.)
Inspiratory reserve volume	The amount of air that can be inhaled beyond the normal indrawn breath (~2900 ml.).
Expiratory reserve volume	The amount of air that can be exhaled beyond the normal exhaled breath (~1100 ml.).
Vital capacity	The amount of air that can be inhaled in the deepest breath and exhaled completely (~4500 ml.). Vital capacity = tidal volume + inspiratory reserve volume + exploratory reserve volume.
Residual volume	The amount of air that cannot be expelled from the lungs no matter how hard one tries (~1200 ml.).
Total lung capacity	The amount of air that can be accommodated by the lungs. Total lung capacity = vital capacity + residual volume

Table 6. A comparison of preflight and postflight stand test data. Mean BP = mean arterial blood pressure (mm of Hg), HR = heart rate (beats per minute), CO = cardiac output (ml per minute), and SV = stroke volume (ml per beat).

Preflight Merged Event	Mission	Crew Member	Mean BP	HR	CO	SV	Leg Volume	Change	% Change
Supine	SLS-2 L-15	A	92.00	56.00	6000.00	107.14			
Supine	SLS-2 L-15	B	79.33	63.00	6600.00	104.76			
Supine	SLS-2 L-15	C	92.00	43.00	5300.00	123.26			
Supine	SLS-2 L-15	D	87.67	70.00	6100,00	87.14			
Supine	SLS-2 L-15	E	78.67	72.00	5638.00	78.31			
Supine	SLS-1 L-15	F	83.00	52.00	4917.00	94.56			
Supine	SLS-1 L-15	G	71.00	46.00	4732.00	102.87			
Supine	SLS-1 L-15	H	70.00	74.00	6239.00	84.31			
Supine	SLS-1 L-15	I	96.00	77.00	7378.00	95.82			
Supine	SLS-1 L-15	J	76.33	56.00	4461.00	79.66			
Stand 5 Min	SLS-2	A	100.67	82.00	4700.00	57.32		49.60	0.46
Stand 5 Min	SLS-2	B	86.67	86.00	5100.00	59.30		628.60	6.72
Stand 5 Min	SLS-2	C	84.00	62.00	4400.00	70.97		604.80	6.42
Stand 5 Min	SLS-2	D	87.33	86.00	5200.00	60.47		290.10	3.56
Stand 5 Min	SLS-2	E	92.67	86.00	4157.00	48.34		-88.10	-0.98
Stand 5 Min	SLS-1	F	82.33	70.00	4490.00	64.14		365.70	4.49
Stand 5 Min	SLS-1	G	77.67	73.00	4287.00	58.73		1031.30	10.18
Stand 5 Min	SLS-1	H	79.33	96.00	4531.00	47.20		301.40	3.29
Stand 5 Min	SLS-1	I	114.00	98.00	5900.00	60.20		-6.70	-0.07
Stand 5 Min	SLS-1	J	77.67	66.00	3581.00	54.26		368.20	4.53
Stand 10 Min	SLS-2	A	117.00	88.00	4600.00	52.27			
Stand 10 Min	SLS-2	B	86.67	80.00	4800.00	60.00			

Stand 10 Min	SLS-2	C	87.33	63.00	4700.00	74.60			
Stand 10 Min	SLS-2	D	72.67	87.00	4400.00	50.57			
Stand 10 Min	SLS-2	E	89.33	93.00	4919.00	52.89			
Stand 10 Min	SLS-1	F	91.33	72.00	4369.00	60.68			
Stand 10 Min	SLS-1	G	81.67	68.00	3932.00	57.82			
Stand 10 Min	SLS-1	H	85.33	96.00	4782.00	49.81			
Stand 10 Min	SLS-1	I	108.67	98.00	5240.00	53.47			
Stand 10 Min	SLS-1	J	79.00	68.00	3443.00	50.63			

Postflight Merged Event R+O Change	**Mission**	**Crew Member**	**Mean BP**	**HR**	**CO**	**SV**	**Leg Volume**	**Change**	**% Change**
Supine	SLS-1	A	85.67	76.00	6612.00	87.00	8140.90	640.70	7.87
Supine	SLS-1	B	88.00	48.00	4719.00	98.31	7838.10	28.80	0.37
Supine	SLS-1	C	81.00	44.00	3889.00	88.39	9839.30	74.10	0.75
Supine	SLS-1	D	75.33	92.00	6947.00	75.51	8842.10	149.90	1.70
Supine	SLS-1	E	99.00	76.00	7995.00	105.20	9396.00	-6.70	-0.07
Supine	SLS-2	F	82.00	61.00	4497.00	73.72	7768.60	256.00	3.30
Supine	SLS-2	G	90.00	71.00	5914.00	83.30	9472.60	480.50	5.07
Supine	SLS-2	H	83.67	61.00	5221.00	85.59	7474.70	261.90	3.50
Supine	SLS-2	I	103.67	86.00	6112.00	71.07	8178.00	333.10	4.07
Supine	SLS-2	J	69.67	64.00	5921.00	92.52	9507.30	501.40	5.274
Stand 5 Min	SLS-1	A	96.67	104.00	-	-	8781.60		
Stand 5 Min	SLS-1	B	75.00	96.00	4824.00	50.25	7866.90		
Stand 5 Min	SLS-1	C	65.00	100.00	3484.00	34.84	9913.40		
Stand 5 Min	SLS-1	D	83.67	126.00	4991.00	39.61	8992.00		
Stand 5 Min	SLS-1	E	114.00	98.00	5900.00	60.20	9389.30		
Stand 5 Min	SLS-2	F	83.67	89.00	2947.00	33.11	8024.80		

Stand 5 Min	SLS-2	G	102.67	127.00	4825.00	37.99	9953.10		
Stand 5 Min	SLS-2	H	77.00	140.00	3615.00	25.82	7736.60		
Stand 5 Min	SLS-2	I	106.33	123.00	3218.00	26.16.	8511.10		
Stand 5 Min	SLS-2	J	81.33	101.00	4336.00	42.93	10008.70		
Stand End 8 Min	SLS-1	B	71.33	101.00	5357.00	53.04			
Stand End 9 Min	SLS-2	J	78.33	104.00	3850.00	37.02			
Stand End 10 Min	SLS-1	E	108.67	98.00	5240.00	53.47			
Stand End 10 Min	SLS-1	F	87.67	104.00	2935.00	28.22			
Stand 10 Min(with help)	SLS-2	G	103.33	126.00	3046.00	24.17			
Stand 10 Min	SLS-2	I	112.67	123.00	3670.00	29.84			

Figure 24. The principle behind the electrocardiograph involves the transmission of ultrasound waves into a body using a transducer. The sound waves bounce off the heart and are reflected back into the transducer, which also serves as a receiver. The receiver creates an image from the reflected sound waves and the image is displayed on a monitor.